EXECUTIVE SUMMARY

An Energy Efficient Approach for Radon Management In a HVAC Environment

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DEDICATION

To my Heavenly Father whose blessing;

my wife Grace whose encouragement;

my children Esther, Simon and Anna whose understanding

made this study possible

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ABSTRACT

Radioactive radon gas, after being released from rocks, soils and building structures, can pose a significant health threat to the building occupants. This is of particular concern in tight HVAC (Heating, Ventilating and Air-Conditioning) serviced buildings where there is re-circulating air with limited fresh air intake. A thorough survey was initiated at the Hong Kong University of Science and Technology (HKUST) in 1996 and results indicate a radon average concentration of 107 Bq/m^3, which is approximately 50% of the World Health Organisation's (WHO) recommended standard (200 Bq/m^3). About 10% of the measurements were in excess of this WHO limit, while 46% of the samples also showed average peak radon concentrations (264 Bq/m^3) in excess of this WHO limit.

To overcome these elevated indoor radon concentrations, their characteristics at HKUST was studied. Radon level was found to increase linearly as a function of the length of the HVAC shut off period, and decrease exponentially upon system resumption. *Radon level predictive models* were developed after a series of room chamber experiments with modification factors defined to account for the indoor sinks in an effort to enhance the accuracy and applicability of the *models*.

Following a campus-wide energy audit, two energy-efficient radon management approaches were derived from the *predictive models* and were subsequently integrated into the existing HKUST operations. The first was defined as an *Active Radon Control Approach (ARCA)*, where HVAC operation schedules were modified to yield an energy saving potential of around HK$2.7 Million a year. *ARCA* is optimised to reduce the radon dose to the HKUST occupants following the radiation protection principle of "As Low As Reasonably Achievable (ALARA)", and with considerations of economical and operational constraints.

The other was a *Passive Radon Control Approach (PRCA)* using Polyurethane-based (P-u) paint to cover building material surfaces to reduce the radon emission. Climate chamber and room chamber experiments were carried out to evaluate the effectiveness of the *PRCA* in sealing up the radon entry routes with P-u paint in a HVAC environment. The resulting dose reduction and the corresponding health benefits were also evaluated. The results confirmed indoor radon levels can be effectively reduced to hold below the WHO limit. However, an investment of approximately HK$57 Million is required to yield an annual energy saving potential of HK$5 Million with a discounted payback period of 13 years.

Chapter 1
INTRODUCTION

1.1 RADON FUNDAMENTALS

The radionuclides formed within the natural decay series of Uranium-238 are principally radioisotopes of heavy metals. There is one link of this decay series which is a radioisotope of the noble gas radon[1]. Radon, a naturally occurring, colourless, odourless, almost chemically inert and radioactive gas, can be released from surfaces of rocks, soils and building structures into the air[1]. It decays to radioactive daughters, in the form of short-lived radioactive particles, which can remain suspended in the air. When these particles are inhaled, they irradiate the human lungs and increase the risk of developing lung cancer. This risk increases as the level of radon and the duration of exposure increase[2]. Radon-222 (^{222}Rn) itself has a radioactive half-life of 3.8 days[1].

The major uranium decay chain from Uranium-238 (^{238}U) to Radon-222 is shown in *Fig 1-1*.

$$^{238}\mathrm{U} \rightarrow \underset{\text{(Thorium-234)}}{^{234}\mathrm{Th}} \rightarrow \underset{\text{(Protactinium-234)}}{^{234}\mathrm{Pa}} \rightarrow {}^{234}\mathrm{U} \rightarrow \underset{\text{(Thorium-230)}}{^{230}\mathrm{Th}} \rightarrow \underset{\text{(Radium-226)}}{^{226}\mathrm{Ra}} \rightarrow {}^{222}\mathrm{Rn}$$

Fig 1-1 Major decay chain from Uranium-238 to Radon-222

1.2 RADON HEALTH RISK

According to a Report of the United Nation Scientific Committee on the Effects of the Atomic Radiation (UNSCEAR), radon and its daughters contribute about 50% of the effective dose equivalent to human beings from all natural radiation sources[3].

While the lung cancer risk to uranium miners has been known for a long time, the possible influence of radon on lung cancer risk to the general public was discovered much more recently[4]. The lifetime risk for lung cancer due to lifelong exposure to radon and its decay products was estimated by the National Radiological Protection Board (NRPB)[5] of United Kingdom as shown in *Table 1-1.*

More details are given in the *EngD Portfolio Submission 1.*

Radon Concentration	*Life Time Risk of Lung Cancer (%)*		
(Bq/m^3)	*Whole Population*	*Smoker**	*Non-Smoker**
10	0.15	0.5	0.05
20	0.3	1	0.1
40	0.6	2	0.2
200	3	10	1
400	6	20	2

*On the assumption that one person in four smokes about 15 cigarettes a day.

Table 1-1 Lifetime risk of lung cancer for radon exposure[5]

1.3 HONG KONG SITUATION

Exposure to gamma rays from natural radionuclides occurs outdoors and indoors. Surveys by direct measurements of dose rates were arranged by the UNSCEAR during the last few decades in many countries. *Fig 1-2* summarises the doses for over half of the world population. National averages range from 20 to 190 nGy h^{-1} and the population-weighted averages[6] are 57 and 80 respectively for outdoors and indoors. However, the absorbed dose rate in Hong Kong for indoor air was found to be at the top end (190 nGy h^{-1} [6]) which appears to correlate with high thorium-bearing and uranium-bearing materials etc. used for constructing homes and buildings.

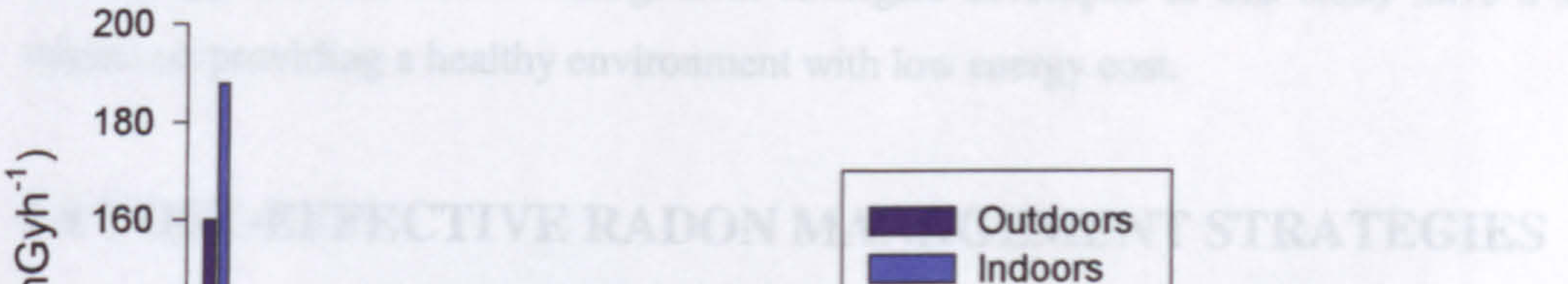


Fig 1-2 Absorbed dose rates in air from terrestrial gamma radiation ranked according to levels outdoors[6]

In 1995, the Hong Kong Environmental Protection Department (HKEPD) reported that a high level of natural radon was found emitting from soil, rock or from building material such as concrete made with granite[7]. In fact, granites are common in Hong Kong and are widely used as a major material to produce concrete for building construction. An official territory-wide survey reported the average indoor radon concentration measured in Hong Kong was 98 Bq/m^3, which is double the global average[6] of 42 Bq/m^3

Due to land being limited in Hong Kong, most homes and offices are in multi-storey buildings. These buildings are made of concrete, which contains crushed granite. Granite releases radon gas, which is re-circulated by the HVAC system of the "tight" buildings, resulting in occupants' exposure to this radioactive gas. Due to the high utility consumption of the HVAC system, the building operators are becoming more conscious about energy conservation. The energy-efficient radon management strategies developed in this study have a significant impact on providing a healthy environment with low energy cost.

1.4 COST-EFFECTIVE RADON MANAGEMENT STRATEGIES

Radon control measures in a HVAC environment, as to be explored in the following Chapters of this Executive Summary, involve two major management strategies, namely,

The *Active Control Approach* - To reduce radon levels after radon enters the HVAC serviced environment, and,

The *Passive Control Approach* - To prevent radon from entering the HVAC serviced environment.

In the UK, studies[8] on the durability of various radon remedial actions demonstrated that, in general, passive control methods using paint sealant and coverings remained effective for a long period of time. Figures show the effectiveness of the remedial actions on 45 houses, which remained remarkably stable[8] over the five-year period of the studies. Polyurethanes constitute a group of polymers with highly versatile properties[9] and P-u paint coating gives very high wear resistance[10] and is capable of creating durable surface seal[11]. In 1994, the American Society for Testing and Materials (ASTM) regarded Polyurethane as a suitable elastomeric joint compound, based on its properties of strong adhesion to concrete under difficult conditions, long service life, and good elasticity[12]-[13]. The high effectiveness of P-u paint coating in reducing radon entry rate from building material surfaces has also been confirmed in recent radon studies[14]-[15]. With P-u paints' properties of being durable, having a long service life, and an effective barrier against radon entry, the use of this paint to reduce indoor radon exposures over a long period of time is among the best choices of *Passive Control Approach.*

Fig 1-3 and *Fig 1-4* show the university buildings used in this study. *Active* and *Passive Radon Control Approaches* have been reviewed successfully in several published papers of Chan et al.[16]-[21]. Details are given in Chapter 4 and 5 of this Executive Summary as well as the *EngD Portfolio Submission 4*.

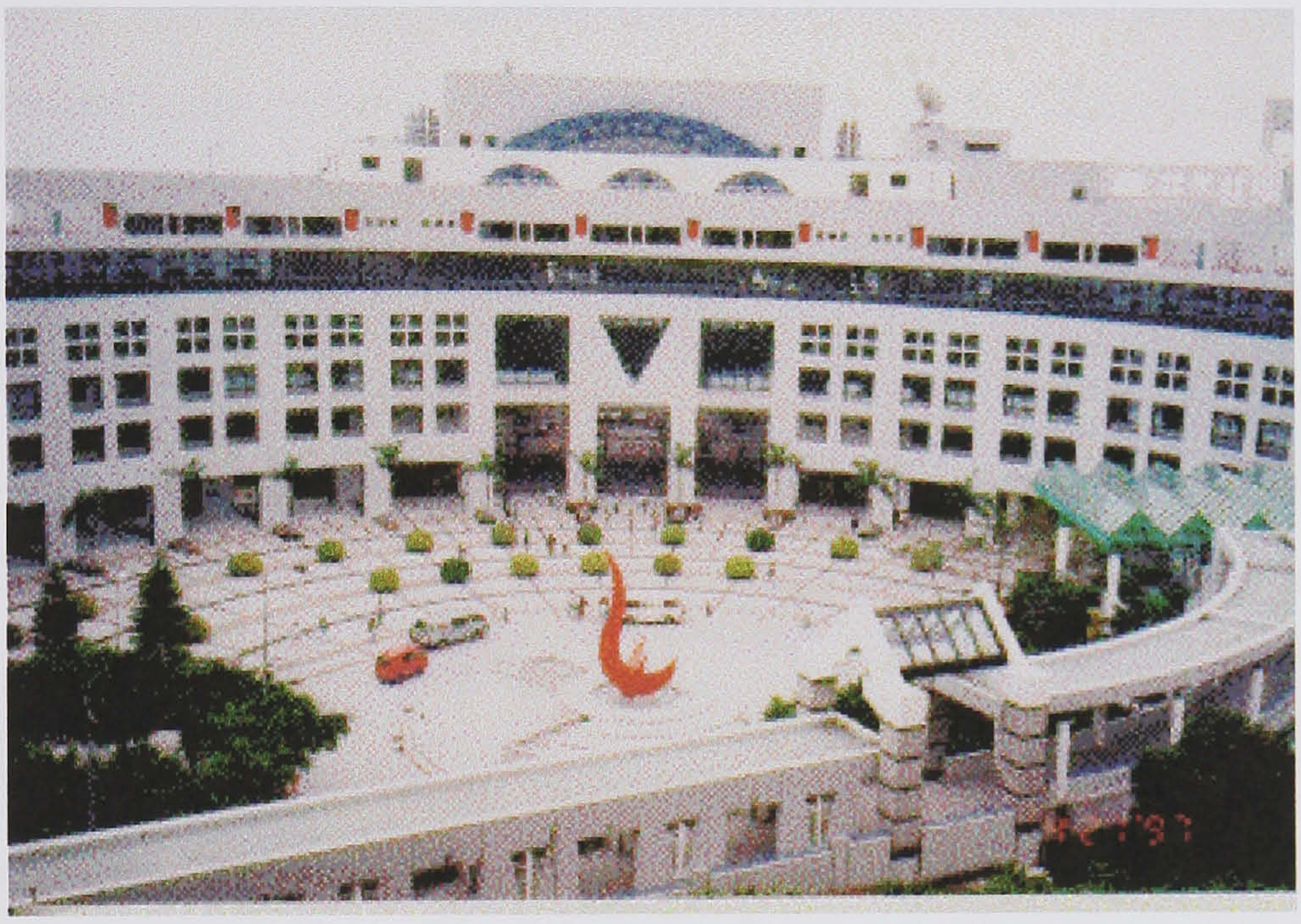


Fig 1-3 Academic & laboratory buildings serviced by the HVAC system

Fig 1-4 Main entrance and administration buildings of HKUST

Although the major objectives of this EngD Project have focused on energy savings and simultaneous management of indoor radon concentrations in a HVAC environment, an assessment of the resulting health risk and radiation dose reduction considerations for the university occupants has also been carried out (See Chapter 6). This evaluation process follows the important basic radiation protection principle of ALARA (as low as reasonably achievable).

1.5 CONCLUSIONS

1. The average indoor radon concentration in Hong Kong is double the global average. The message of health risk associated with the radon exposure has to be communicated properly to the general public of Hong Kong.

2. The development of effective energy-efficient approaches to control indoor radon is a key to success in managing the problem effectively and with a good balance of the health risks and financial costs involved.

3. The major objective of this EngD study is to identify cost-effective ways to address the radon issue. The results, which will be presented in the following Chapters of this Executive Summary, include an *Active Radon Control Approach* using "Cost-effective HVAC operation scheduling" and a *Passive Radon Control Approach* using "Polyurethane-based paint treatment on internal surfaces of the HVAC environment".

Chapter 2

RADON ASSESSMENT

2.1 AN OVERVIEW

This Chapter describes the assessment of radon concentrations in the HVAC serviced environment of the Hong Kong University of Science of Technology (HKUST). Ninety rooms with various configurations were selected at random and evaluated in detail. A time-integrated active sampling instrument and a passive charcoal canister radon detecting system were used for the study. With the central HVAC system in the normal operating mode, data on location characteristics, as well as average and peak radon concentrations were collected and analysed.

The results indicated that radon concentrations increased gradually as a function of the length of the HVAC shut off period. In addition, after the HVAC system was resumed, radon concentrations dropped rapidly. While the average radon level (107 Bq/m^3) for all samples was approximately 50% of the World Health Organisation's (WHO) recommended level (200 Bq/m^3), about 10% of the readings were in excess of this WHO limit. Forty-six percent of these samples also showed an average peak radon concentration (264 Bq/m^3) which exceeded this WHO limit. Major factors, which influenced the results, were identified and evaluated. Full details are given in the *EngD Portfolio Submissions 1 and 2.*

2.2 MATERIALS AND METHODS

Investigated Items and Indicators

1. Daily average concentration of indoor radon (Bq/m^3).

2. Daily peak concentration of indoor radon (Bq/m^3).
3. Room location or construction characteristics:
   a. Is the room in contact with ground soil?
   b. Does the room have a fume cupboard (a laboratory facility to exhaust fume)?
   c. How many hours per day does the HVAC system operate?
   d. When does the HVAC cease to operate at night? (Clock)

Selection of the Sampling Locations in HKUST

Ninety locations in HKUST were selected randomly for investigation. They included:

a. *Offices*: 30. (With FC supply; average room size of 210 m^3)
b. *Classrooms*: 16 (With AHU/FC supply; average room size of 147 m^3)
c. *Laboratories*: 15 (With AHU/FC supply; average room size of 160 m^3)
d. *Workshops & stores*: 13 (With AHU/FC supply; average room size of 317 m^3)
e. *Corridors & lobbies*: 6 (With AHU/FC supply or natural ventilation)
f. *Others*: 10 (With AHU/FC supply or natural ventilation)

AHU and FC stand for, respectively, Air Handling Units and Fan Coil Units, which are major components of the HVAC system. Both are part of the air distribution system with the majority of the indoor air in re-circulation and a minimum of fresh air being replenished from outdoors.

Instrumentation for Radon Measurements

1. <u>The Measuring Instruments</u>
   a. A time-integrated active continuous monitoring sampler known as "RAD7 Professional Continuous Radon Gas Monitor (RAD7)" made by the Niton Corporation in the United States of America (USA) was used. After connection with the power supply, air is continuously pumped through a set of filter elements; a detection unit measures radiation from airborne radon daughters and other background beta and gamma radiation. The RAD7 is

shown in *Fig 2-1*. More details, including operation procedures of the equipment and a sample printout, are also given in *Appendix A*.

b. A passive sampling system, known as "Radon-II Counting System for Activated Charcoal Canister (Charcoal Canister)" made by the U.S. Nucleus Incorporation, was also used in this study. The charcoal canisters consist of tightly sealed packages of activated charcoal that allow air to diffuse through them when the caps are removed. The charcoal attracts radon and radon daughters start to accumulate in the canister due to radioactive decay. After the canisters were exposed for two days, they were sealed and sent to the Radon-II Counting System for analysis. The Radon-II Counting System is shown in *Fig 2-2*.

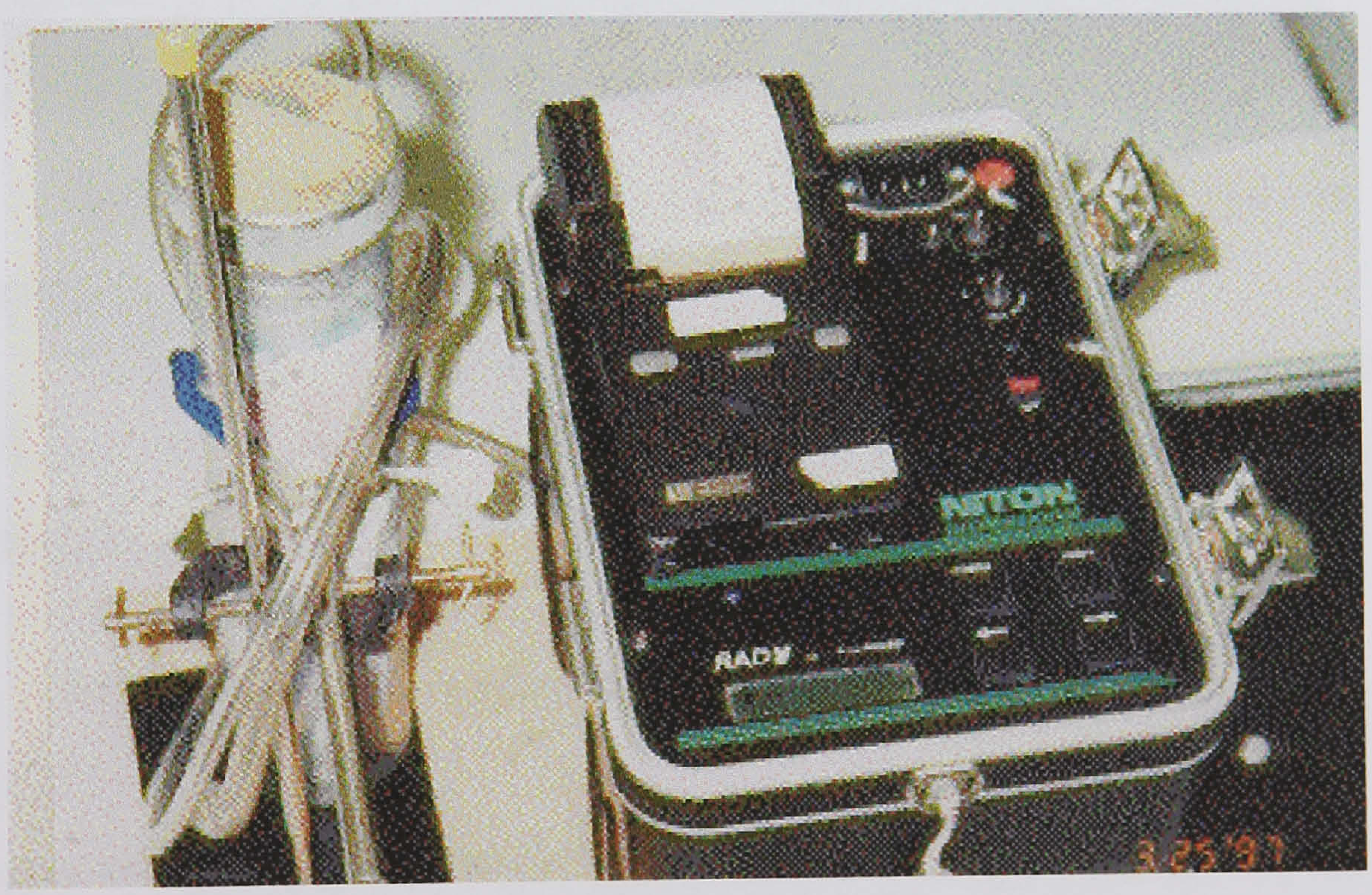


Fig 2-1 RAD-7 Continuous Radon Gas Monitor to measure indoor radon levels

2 <u>Pre-sampling Preparation</u>

a. For better accuracy, the charcoal canisters were dried in a furnace to remove the moisture content before the actual sampling. Baseline measurements were taken using the Radon-II Counting System before the sampling study.

b. The RAD7 Professional Continuous Radon Gas Monitor had been properly calibrated approximately 6 months before the study.

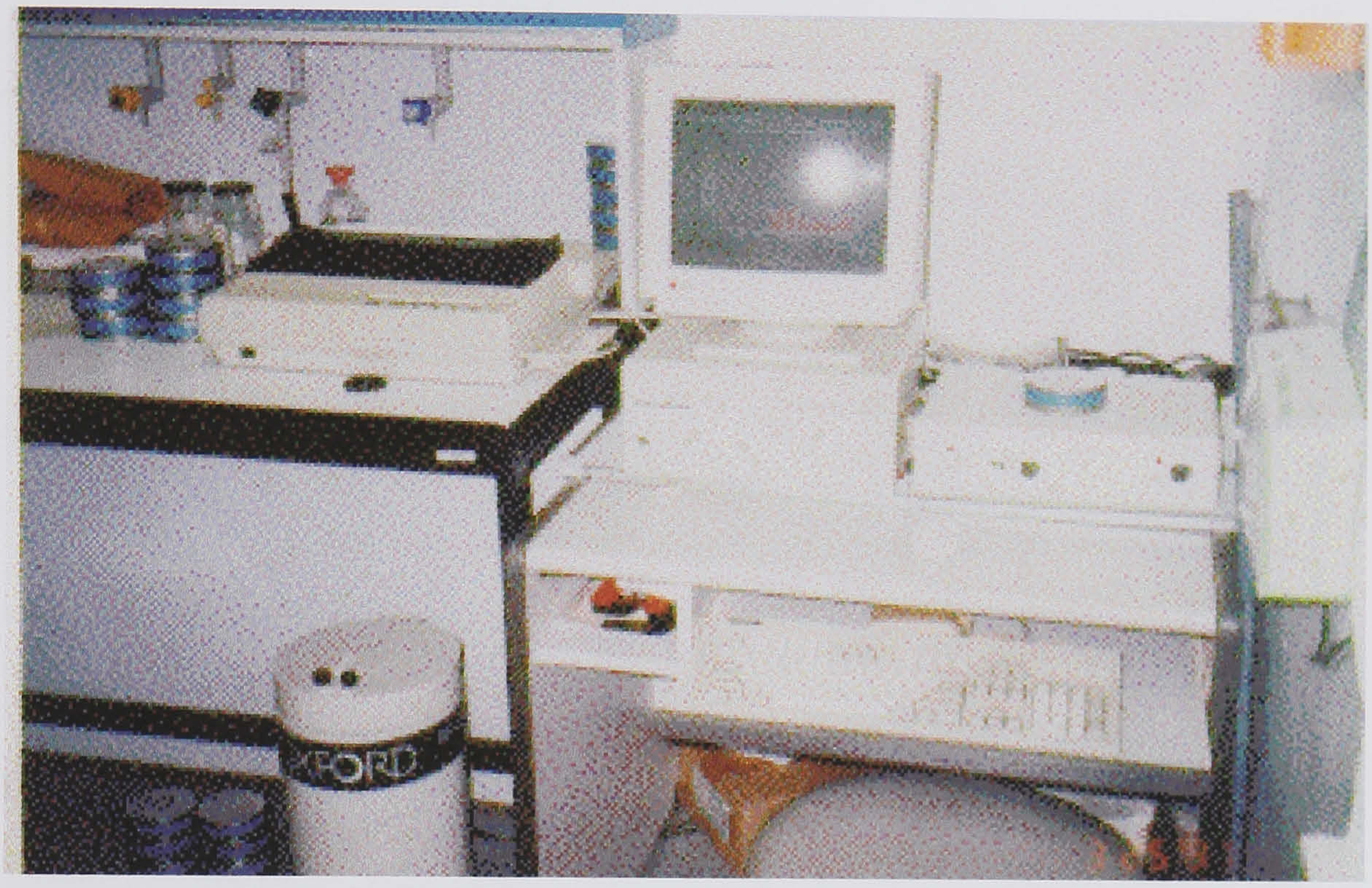


Fig 2-2 Radon-II Counting System to measure radon levels of charcoal canisters

3 <u>Samplers Set-up</u>

The samplers were set up in rooms at approximately one metre above ground and at locations one metre away from all walls, HVAC inlets and exhausts.

4 <u>Measurement Intervals</u>

a. Charcoal Canisters: 24 to 48 hours continuously;

b. RAD7: 24 or 48 hours with samples taken at 30 or 60 minutes intervals.

2.3 RESULTS

Characteristics of Radon Concentrations in terms of Distribution Patterns

The frequency distribution pattern of indoor radon measurements for the HVAC environment of HKUST is shown in *Fig 2-3*. The pattern is similar to the results cited in other literature[22],[23]. When compared to the measurements in non-residential premises as reported by the Hong Kong Environmental Protection Department[25],[26] (HKEPD), the frequency distribution of our data in each concentration range was almost identical[16],[20]. More details are given in the *EngD Portfolio Submission 2*.

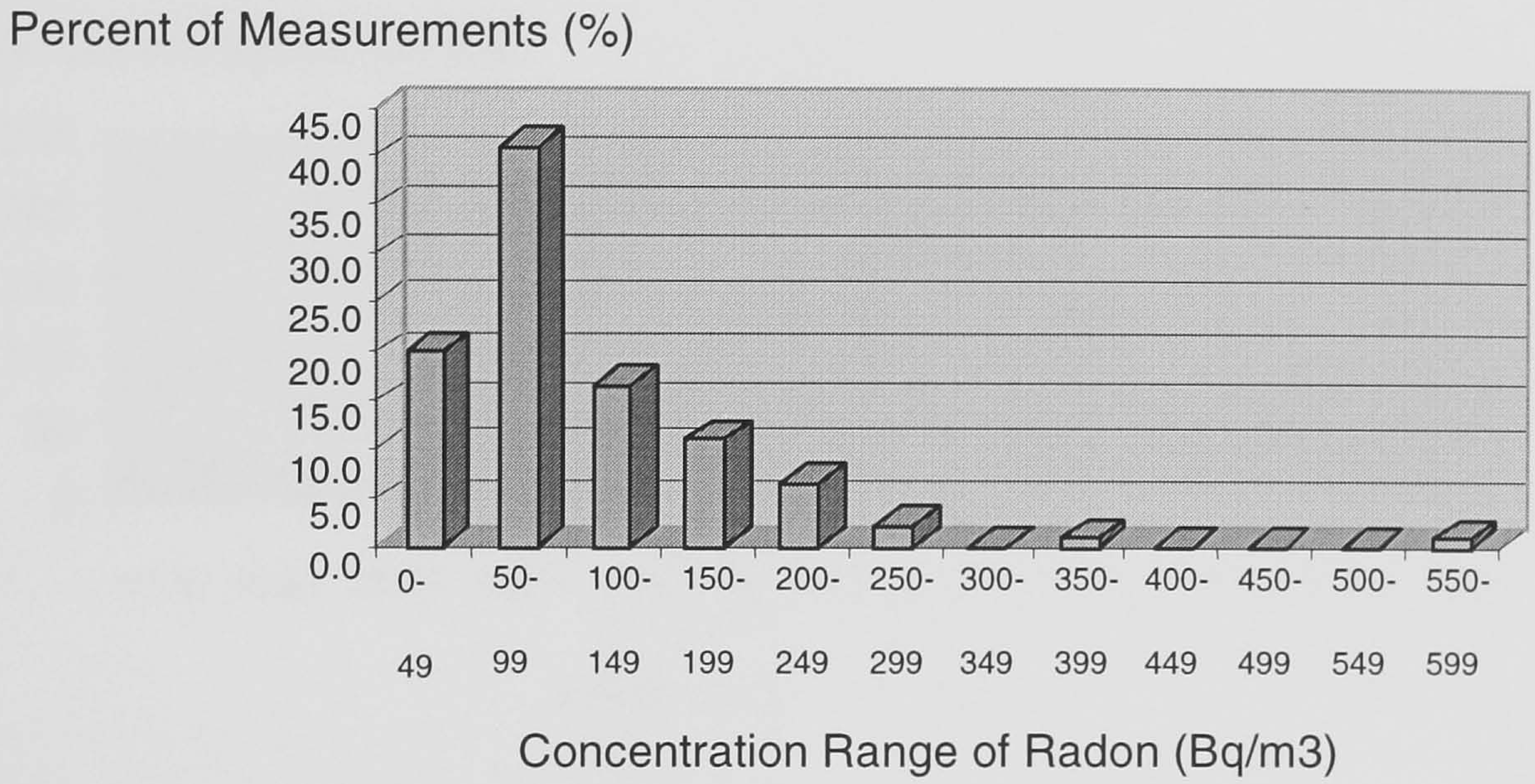


Fig 2-3 Frequency Distribution of Indoor Radon Measurements in HKUST

Characteristics of Radon Concentrations in terms of Daily Variation Patterns

From the measured data, there are two different types of daily variation patterns of indoor radon concentrations. *Fig 2-4* presents a typical pattern for the majority of rooms in the HVAC serviced areas. *Fig 2-5* shows those few areas in campus with only natural ventilation. The results demonstrated that over 95% of areas, surveyed in this experiment, fit the pattern illustrated in *Fig 2-4*. The lowest radon level was obtained immediately prior to switching off the HVAC system after a full period of operation and the highest level occurred at the time immediately before it resumed operation the next morning. The radon concentration was observed to increase gradually during the switched-off period of the HVAC system. It then appeared to decrease rapidly[16],[20] once the system was resumed at 9:00 am in the morning.

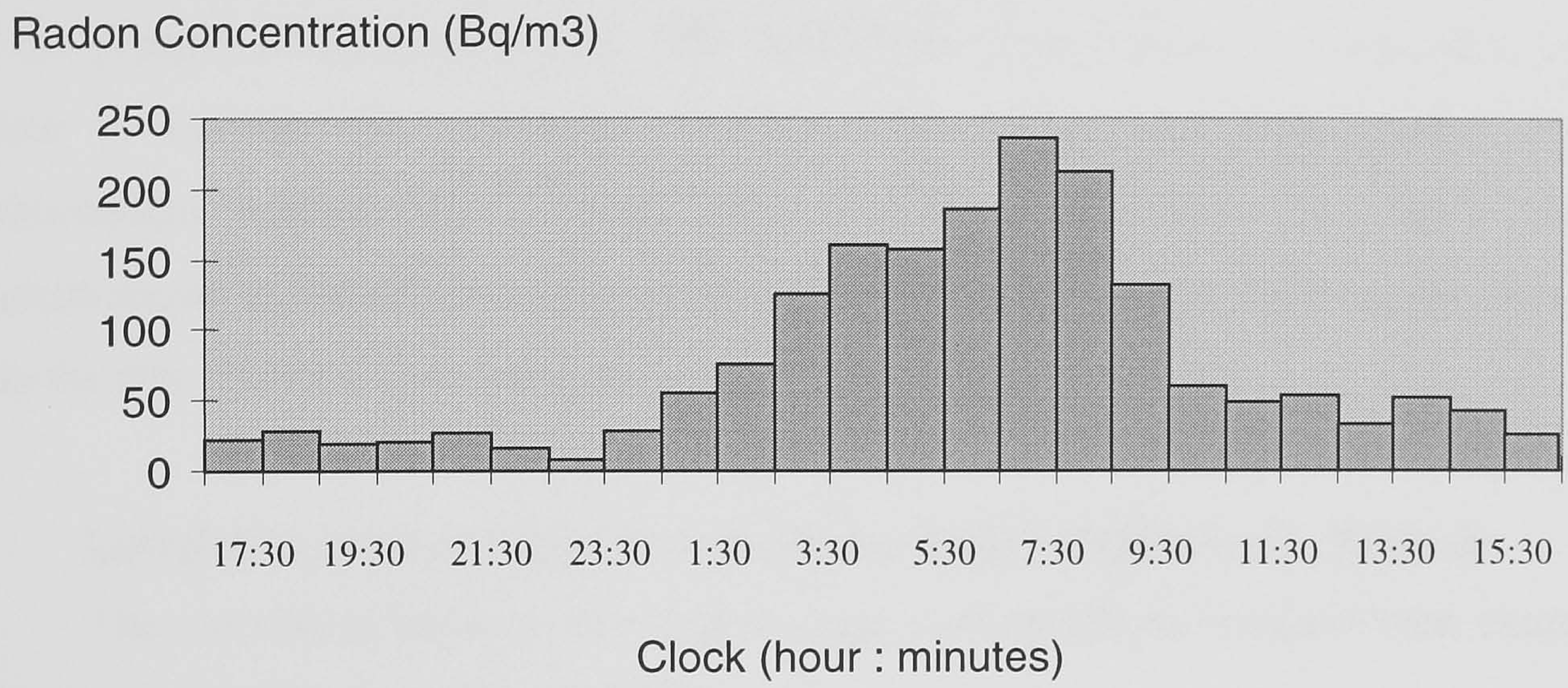


Fig 2-4 The Main Pattern of Daily Variation of Indoor Radon Concentrations in Rooms with Ventilation

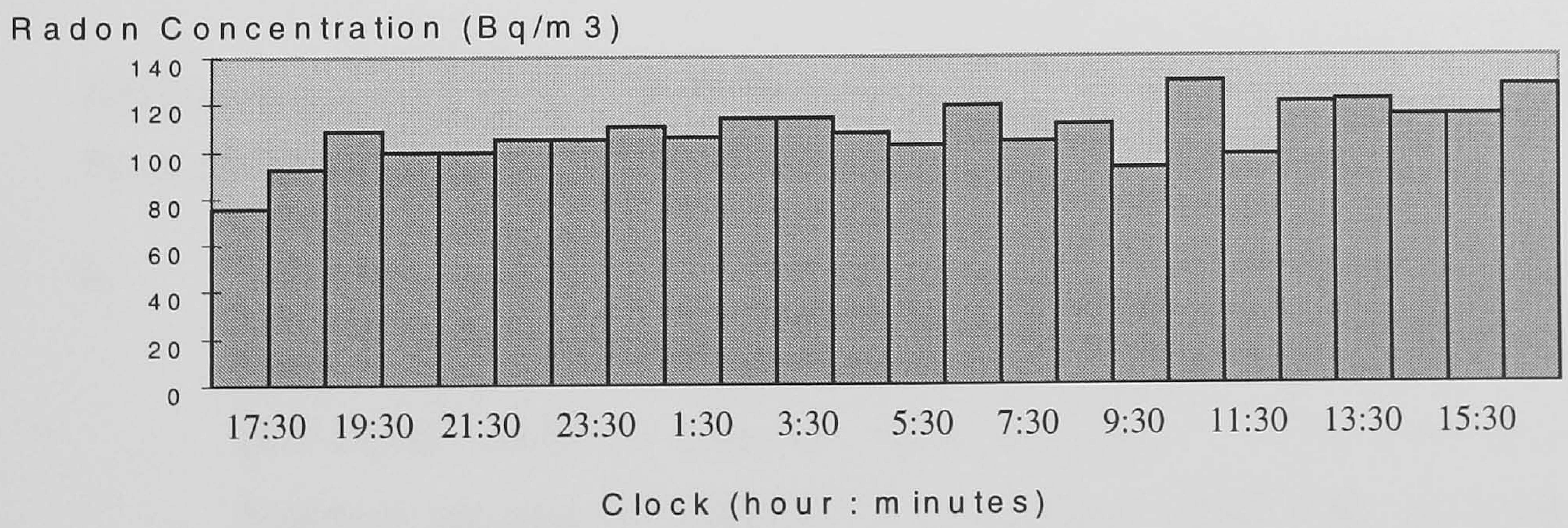


Fig 2-5 The Pattern of Daily Variation of Indoor Radon Concentrations in Rooms without Ventilation

Defining the Average & Peak Radon Concentrations at HKUST

In this sampling study, in order to achieve the mean radon concentrations in a number of different building locations at one time, charcoal canisters were used as the main sampler for the process of data collection. The RAD7 was also used as a comparative measuring device to evaluate the correlation between the average and peak levels. Using this mathematical relationship, a *model* was developed to predict the daily peak radon concentrations in the HVAC environment of HKUST[16],[20] by correlating the data obtained from the two different measuring devices.

1. Correlation between Charcoal canister and RAD7 Measurement Methods

The correlation between the daily average concentrations obtained from charcoal canisters and RAD7 was demonstrated:

$$C_{Rad7} = 11.24 + 1.25\, C_{canister} \qquad (1)$$

$$(r = 0.97,\ r^2 = 0.94,\ p<0.01)$$

Where, C_{Rad7} and $C_{canister}$ stand for radon concentrations obtained by the RAD7 monitor and charcoal canisters respectively. This *model (1)* can be used to correlate the results of the two measurement methods. Full details are given in the *EngD Portfolio Submission 2.*

2 Assessment of Radon Concentrations at HKUST

From the results of our sampling study, we observed:

a. The daily average radon concentration of rooms sampled at HKUST was 107 Bq/m^3 which is significantly lower than the WHO Radon Action Level[24] of 200 Bq/m^3 ($t=10.53$, $p<0.01$). This 200 Bq/m^3 action level is also the Standard adopted by HKEPD[2.5]. However, about 10% of these rooms showed radon concentrations in excess of the WHO Radon Action Level.

b. The average peak radon concentration of rooms sampled was 264 Bq/m^3 which is significantly higher than the WHO Radon Action Level ($t=3.12$, $p<0.01$). Forty-six percent of the rooms evaluated showed peak radon concentrations in excess of the WHO Radon Action Level of 200 Bq/m^3.

3. Correlation between Average and Peak Radon Concentrations

The correlation between the daily average and daily peak concentrations measured by RAD7 is shown in *Fig 2-6*. The mathematical relationship was modelled as:

$$C_{peak} = 17.22 + 2.31\ C_{daily} \qquad (2)$$

$$(r = 0.96,\ r^2 = 0.91,\ p<0.01)$$

Where, C_{peak} and C_{daily} stand for peak and daily radon concentrations measured respectively in this study. By employing *models (1)* and *(2),* one can predict the peak radon concentrations from the daily average radon concentrations measured by the simple charcoal canister method.

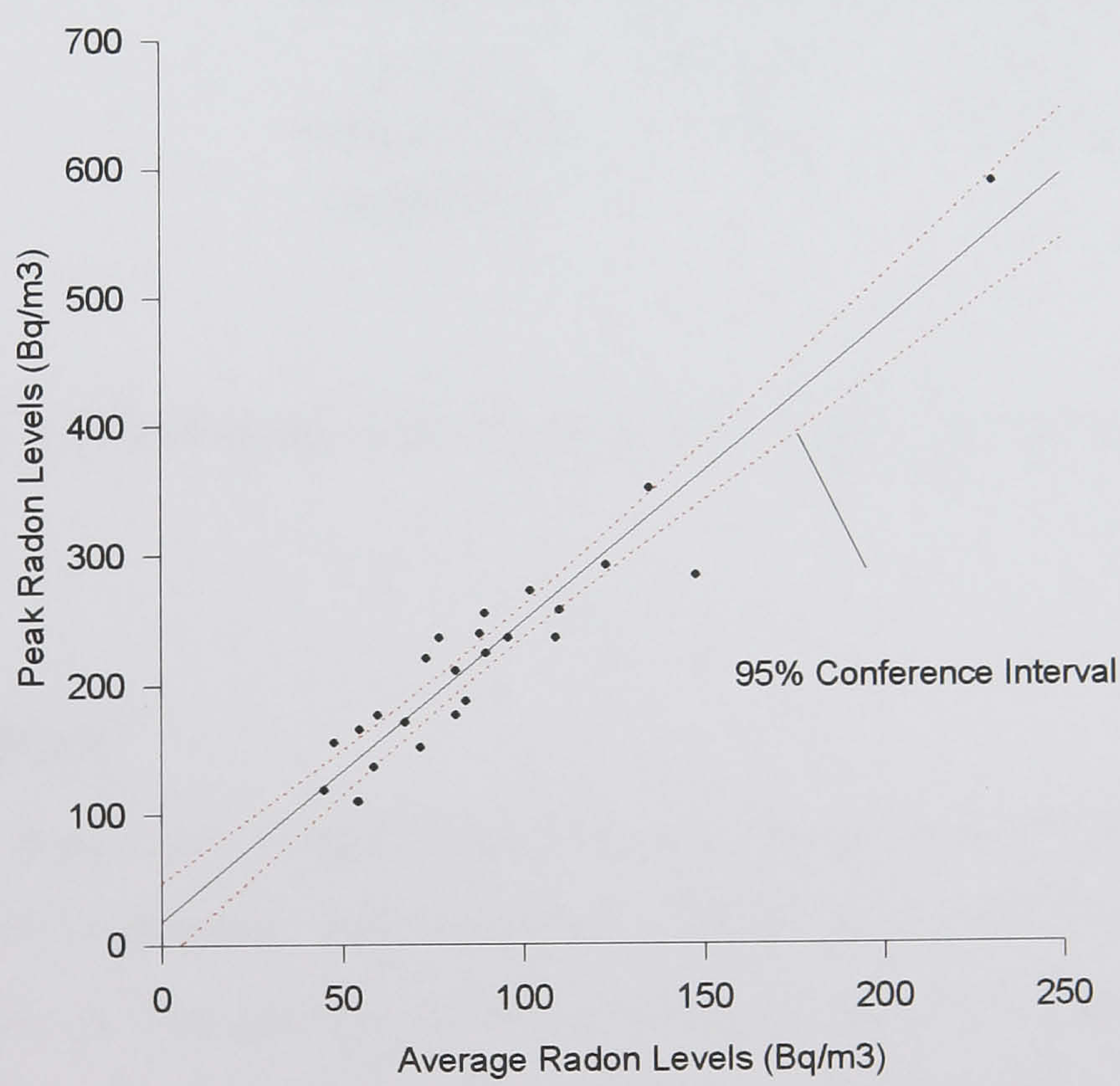


Fig 2-6 Regression between Daily Average and Peak Radon Levels

4. Factors Influencing the radon concentrations

The major factors influencing radon concentrations of the HVAC environment of HKUST during the study are shown in *Fig 2-7*. These include contact with ground where radon from ground soil is a significant factor and the presence of fume cupboards, which exhaust indoor air without re-circulation, thus helping to lower indoor radon concentration.

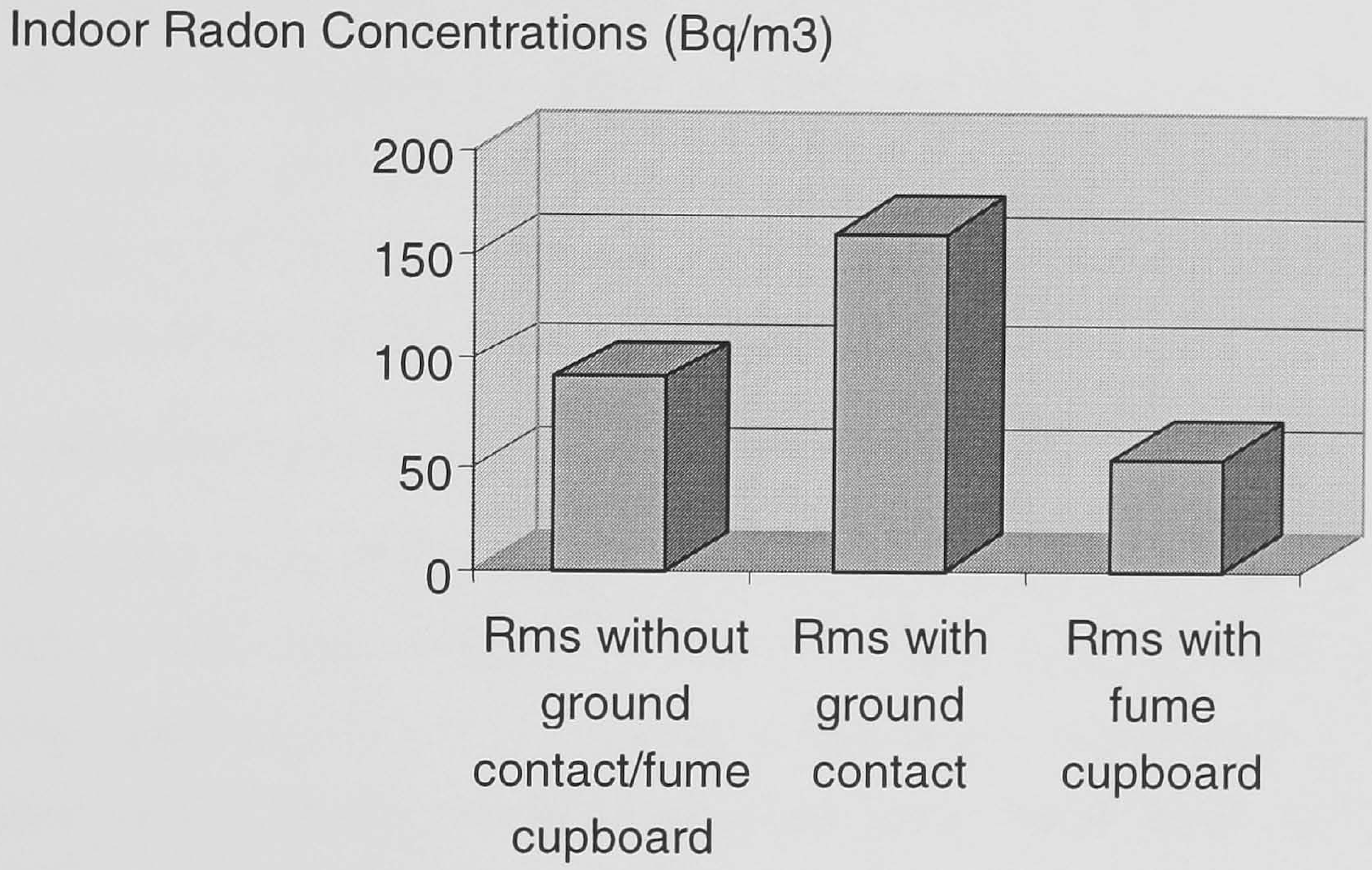


Fig 2-7 The Factors Affecting the Indoor Radon Concentrations

2.4 DISCUSSION

a. Representative comparison of HKUST Radon measurements with HKEPD data

The results of a sampling study reported by HKEPD in 1994[26] are summarised in *Table B-1* of *Appendix B*. The average concentration for all sampled premises in Hong Kong was reported at 98 Bq/m^3 and that observed at HKUST was 107 Bq/m^3. Statistical analysis ($t=0.99$, $p>0.05$) confirms there is no significant difference between these two sets of data. As the HKEPD data were obtained from a representative territory-wide indoor radon survey in Hong Kong, the *models* and the subsequent *approaches* derived in Chapter 2 and 4 of this Executive Summary appear to be applicable to apply to the general Hong Kong environment.

b. *Comparing HKUST average measurement with reference exposure levels from other countries and global average measurement*

The average radon level identified at HKUST was compared with published radon reference exposure levels from 11 other countries[27]. Details of these reference levels are listed in *Table B-2* of *Appendix B.* These included exposure limits from Netherlands (20 Bq/m^3), Luxembourg (150 Bq/m^3) and USA (150 Bq/m^3) which are compared with the HKUST average of 107 Bq/m^3. Moreover, the HKUST average measurement was found to be double the global average measurement of 42 Bq/m^3.

c. *Factors influencing Indoor Radon Concentrations at HKUST*

As described in the *EngD Portfolio Submissions 1 and 2*, there are several situations in which indoor radon concentrations are affected. These include the source strength of radon bearing materials (soil, water, building materials and natural gas etc.), "structural characteristics" of the building environment which affect radon entry and removal, and meteorological conditions[28]. In our sampling study, we focused specifically on the following:

1. Fume cupboard (structural characteristics)

The impact of fume cupboards on indoor radon concentrations in the sampled rooms was shown in *Fig 2-7.* The radon level in the areas equipped with one or more fume cupboards was significantly lower than those without cupboards ($t=4.08$, $p<0.01$). This can be attributed to increased one-pass exhaust ventilation through these units resulting in a reduction in indoor radon concentrations.

2. Ground Soil Contact (Source strength)

The effect of ground soil contact in the sampled rooms of HKUST was also shown in *Fig 2-7.* Radon concentrations in areas in contact with ground soil were found to be significantly higher than those above ground level ($t=2.68$, $p<0.01$). Details are given in the *EngD Portfolio Submission 2.* This increase could be attributed to the radon released from ground soil resulting in the gas seeping into the indoor environment in addition to that released from the concrete walls.

3. HVAC ON/OFF Duration (Structural characteristics)

By excluding the factors of ground soil contact and fume cupboards, a trend was observed: the longer the HVAC OFF period, the higher the indoor radon concentrations. Statistical analysis confirms a significant correlation between the duration of the HVAC OFF hours and indoor radon concentrations ($Y = 37.68 + 5.26\ X$, $r = 0.2729$, $p<0.05$).

2.5 CONCLUSIONS

The following conclusions can be drawn from this set of sampling studies:

1. There is good correlation between the real-time, active radon sampling results obtained from the RAD7 and that of passive radon sampling results obtained from charcoal canisters. This confirms the value of the inexpensive charcoal canister system for radon monitoring,

2. Using the *model* derived from this set of sampling studies, one can accurately predict peak radon concentrations from average radon levels in the HVAC serviced areas. Both sets of data are useful for engineering control purposes as well as for health risk assessment considerations,

3. The distribution of radon concentrations observed at HKUST matches well with the community data reported by the Hong Kong Environmental Protection Department,

4. While the vast majority of the measured average radon concentrations were within the WHO Action Level, 10% of the data indicated average concentrations in excess of this action level and 46 % of the measured peak concentration readings were above the WHO Action Level.

5. After the HVAC system was turned off, the radon levels in the assessed areas increased gradually as a function of time. However, they decreased rapidly upon the resumption of the HVAC services.

Chapter 3

RADON MODELLING

3.1 AN OVERVIEW

The main purpose of this set of experiments was to investigate the feasibility of applying existing mathematical models for predicting the indoor concentrations of Volatile Organic Compounds (VOC) during ON/OFF modes of the HVAC system to estimate the radon concentration levels. This would allow more effective control of radon levels using the existing HVAC system by which the majority of the indoor air is in re-circulation. Parameters measured included initial radon concentration, emission rate, elapsed time from the HVAC ON/OFF schedule, source decay rate, fresh air exchange rate, radon concentration in fresh air intake, etc. A specific modification factor to account for the sink effect of the chamber environment was applied to the pre-existing VOC models to generate the *radon level predictive model.* This *model* was developed to enable the accurate prediction of radon concentrations at any specific time domain. Through various regression analyses, it was observed that these improved *models* match well with experimental data. The simulated modified mechanism worked well under various indoor ventilation conditions.

3.2 MODELLING

This work involved development and formulation of a *radon level predictive model* in a HVAC environment. The initial stage of this project focused on locating different models commonly used in assessing indoor air quality (IAQ), from the simplest to the more complex models. The effort yielded no available model which is directly applicable to the

HVAC environment of HKUST for predicting the radon concentrations. Some models are useful but require modification to properly fit the environment under study.

Radon Level Predictive Model **during Ventilation-off-hours**

By considering the inert gas characteristics during the period of indoor radon accumulation, the radon emission rate (R) from the surrounding surfaces of the experimental chamber (a field and laboratory emission cell for testing of emissions from indoor coating materials) can be estimated by using the commonly adopted mathematical model for room chamber studies introduced by Nancy F. Roache, et al. [29],[30] in 1996:

$$R_{(t)} = (dC_{(t)}/dt + NC_{(t)})/L \qquad (3)$$

Where:

Parameters	*Description of items and Indicators*	*Units*
$R_{(t)}$	Emission rate of the Indoor Air Pollutant at any elapsed time, t	Bq/m^2-hr
$C_{(t)}$	Concentration of the Indoor Air Pollutant at any elapsed time, t	Bq/m^3
N	Fresh air exchange rate of the room	ACH, /hr
L	Loading factor of the room or indoor environment, (Where, L = S/V and S/V is the room internal surface area / volume)	m^2/m^3, /m

Assuming the natural ventilation rate of the room is small and can be ignored during the night time when its HVAC system has been turned off (ventilation-off-hours):

As $N = 0$, $NC_{(t)} = 0$,

The mathematical model can be transformed into:

$$R_{(t)} = (dC_{(t)}/dt)/L, \qquad R = (C_{(t)}-C_o)/Lt$$

$$C_{(t)} = C_o + RLt \qquad (4)$$

Where,

Parameters	*Description of items and Indicators*	*Units*
C_o	Initial radon concentration in experimental room chamber	Bq/m^3
R	Radon emission rate from experimental room chamber surfaces	Bq/m^2-hr
L	Loading factor of experimental room chamber as before	m^2/m^3, /m
t	Elapsed time while fresh air supply was in termination	hr

This *model (4)* was used to calculate the R in our experiments.

Radon Level Predictive Model **during Ventilation-on-hours**

After a series of model investigation exercises in conjunction with dilution of indoor pollutants within a single room environment, two models appeared to be applicable:

(I) <u>*MODEL "A"*</u>

Mathematical model introduced by P.A. Lawless (1996)[31] is presented in *Fig 3-1.*

By estimating $\underline{RS}_{(t)}$ of VOC in the climate chamber:

With $\underline{RS} = R*S$, $L = S/V$

$$\underline{RS}_{(t)} = \underline{RS}_o \exp(-kt) \qquad (5)$$

Where,

Parameters	*Description of items and Indicators*	*Units*
$\underline{RS}_{(t)}$	Source strength as a function of time	mg/hr
$\underline{RS}_o$	Initial source strength	mg/hr
k	Source decay rate	/hr
t	Elapsed time (variable) during experiment	hrs

The mathematical model which predicts a corresponding time-dependent chamber concentration $C_{(t)}$ is:

$$C_{(t)} = \frac{RS_o}{V(N-k)}[\exp(-kt)-\exp(-Nt)]+C_o \exp(-Nt) \qquad (6)$$

Where,

Parameters	*Description of items and Indicators*	*Units*
$C_{(t)}$	Chamber concentration as a function of time t	mg/m^3
V	Volume of room chamber	m^3
N	Air exchange rate	/hr
$C_{o'}$	Initial chamber concentration	mg/m^3

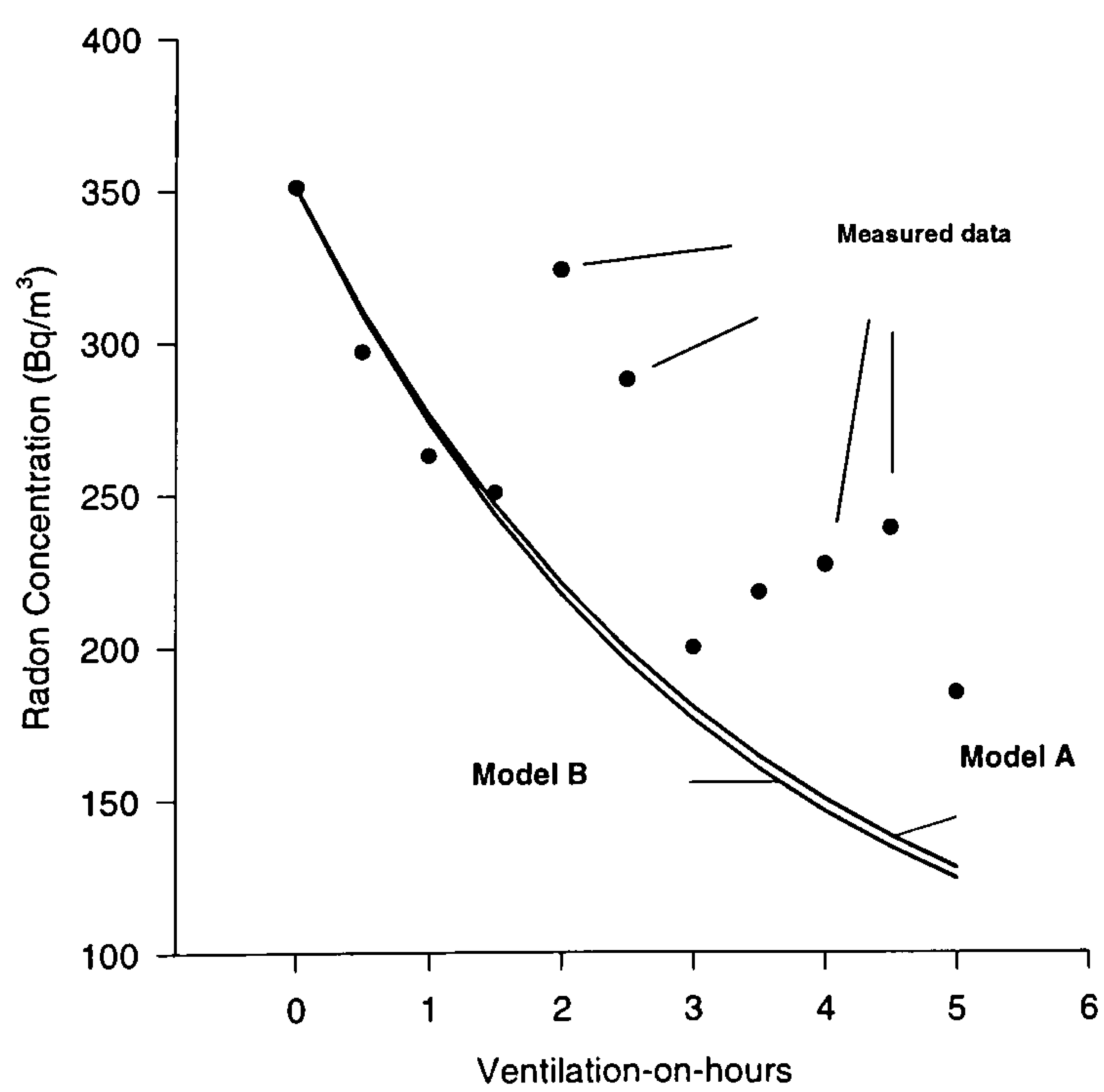
In our experiments, C_{in} existed and the *model (6)* was adjusted to reflect our experimental conditions:

$$C_{(t)} = \frac{RL}{N-k}[\exp(-kt)-\exp(-Nt)]+(C_{o'}-C_{in})\exp(-Nt) \quad +C_{in} \qquad (7)$$

Where,

Parameters	Description of items and Indicators	*Units*
$C_{(t)}$	Radon concentration at t when HVAC in operation	Bq/m^3
C_{in}	Background radon concentration in fresh air	Bq/m^3
$C_{o'}$	Initial radon concentration in test room	Bq/m^3
k	Source decay rate	/hr

The adjusted *model (7)* was used to analyse our field data for evaluation.



Where,
1. Measured data/*Model A:* r=0.7897 and
2. Measured data/*Model B:* r=0.7893

Fig 3-1 Comparing Models A and B (N = 0.30)

(II) *MODEL "B"*

Similarly, another mathematical model, introduced by D. Capra et al. in 1994, was used to evaluate the effect of ventilation rate on radon concentrations in a test chamber[32]. The result is presented in *Fig 3-1.* This *model* was adjusted to take into consideration the parameters encountered in our field tests for comparison purpose.

$$C_{(t)} = \frac{RL + NC_{in}}{N + k} \{1\text{-}\exp[-(N+k)t]\} + C_o \exp[-(N+k)t] \qquad (7a)$$

Both *models A* and *B* are statistically applicable to our situation, however, *model A* appears to be matching marginally better than *model B* during minimal fresh air exchange conditions. Modification of the *model A* was undertaken to accurately reflect the indoor environment under study. The *model* building process also employed a computer simulator to aid the computational aspect of the study. Full details are given in the *EngD Portfolio Submission 3* and the upcoming sections of this Chapter.

3.3 MATERIALS AND METHODS

The Room Chamber

The experimental room chamber selected for this study was a typical office with HVAC service. It was located one floor above ground level at the main campus building. Its dimensions measured 4.95 metres long, 2.77 metres wide and 2.85 metres as shown in the *EngD Portfolio Submission 3.*

With floor coverings and sealed windows, the effective surface area, S, was calculated at 70.8 m^2 and the loading factor, L (S/V ratio) at 1.81 m^2/m^3. A fresh air supply duct was adjustable both in outflow velocity U (m/sec) and area F (m^2), the fresh air exchange rate N (ACH or Air Change/Hour) can be varied from 0.25-4 ACH. With this typical room layout and set-up, radon emission rates (Bq/m^2/hr) obtained during the experiment can be used to simulate other HKUST built environments where HVAC service is provided.

Investigated Items and Indicators

Parameters	*Description of items and Indicators*	*Units*
$C_{(t)}$	Indoor radon concentration at any elapsed time t	Bq/m^3
R	Radon emission rate from room chamber surfaces	Bq/m^2-hr
t	Elapsed time (variable) during experiment	hrs
L	Loading factor of room chamber, where L = S/V	m^2/m^3,/m
S	Surface area of room chamber selected for experiment	m^2
V	Volume of above experimental room chamber	m^3
C_{in}	Background radon concentration in fresh air	Bq/m^3
C	Indoor radon concentration taken during experiment	Bq/m^3
N	Fresh air exchange rate of the room chamber	ACH, /hr
k	Source decay rate	/hr

Measurements of Radon Concentrations

The measuring instrument was the time-integrated continuous monitoring device known as "RAD7 professional continuous radon gas monitor (RAD7)" made by Niton Corporation in United States of America (USA). The RAD7 was set up at the centre of room, one metre from the floor and one metre away from the walls, HVAC inlets and exhausts. Measurement frequency was 30 minutes a cycle, 48 cycles a day.

Measurements of Other Indicators

Fresh air exchange rate (N) was measured by the U*F/V method. Flow velocity was measured by VeloclCalc Model 8350-1 anemometer made by TSI INC in USA. Temperature and humidity were measured by thermo-hygrometer (Model RS 212-540). Atmospheric pressure was measured by Gischard Barometer made in Germany. In these experiments, room temperature, relative humidity and atmospheric pressure were measured in the range of 21.0-23.8 °C, 57.2-60.6 and 757.5-755.3 mmHg respectively.

Schedules during Ventilation-off-hours and Ventilation-on-hours

The experiments for ventilation-off-hours and ventilation-on-hours were both conducted for 12 hours either from 17:00 pm to 5:00 am or 19:00 pm to 7:00 am.

Therefore, the ventilation parameter included 12 ventilation-off-hours and 12 ventilation-on-hours. The measurements for C, t and T were continuously measured and recorded according to RAD7 operational instructions. The experiments were conducted for 5 consecutive nights. The fresh air exchange rates (N) for the experiment during vent-on-hours were set at 0.25, 0.5, 1.0, 2.0 and 4.0 Air change per hour (ACH). However, the actual rates were measured at 0.30, 0.52, 1.12, 2.08 and 4.22 ACH respectively.

3.4 RESULTS

Ventilation-off-hours

The regression *model* for the experiments was found to fit the observed data very well ($r^2 = 0.74$, $r = 0.86$, $p<0.01$). *Fig 3-2* shows one of the data plots for a single period while *Fig 3-3* shows all of the results. More details are given in the *EngD Portfolio Submission 3*.

Assuming $Y = C_{(t)}$; $X = t$,

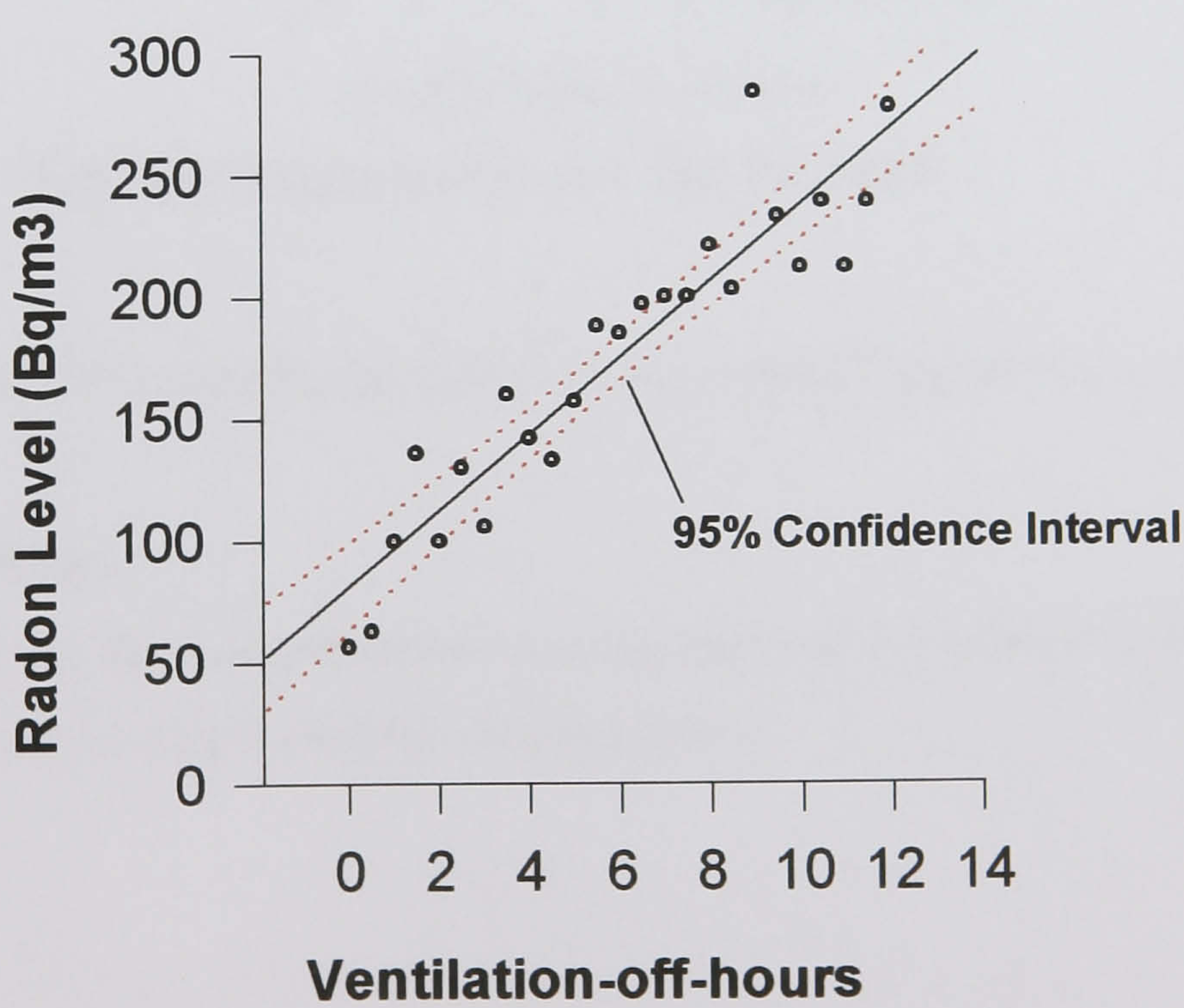


Fig 3-2 Regression for an Individual Period

The data was found in to be in linear regression with relationship Y = a + bX,

As, $C_o = a = 73.82$ (Bq/m^3)

$R = b / L = 15.57/1.81 = 8.6$ (Bq/m^2/hr)

$C_{(t)} = 73.82 + 15.57\,t$

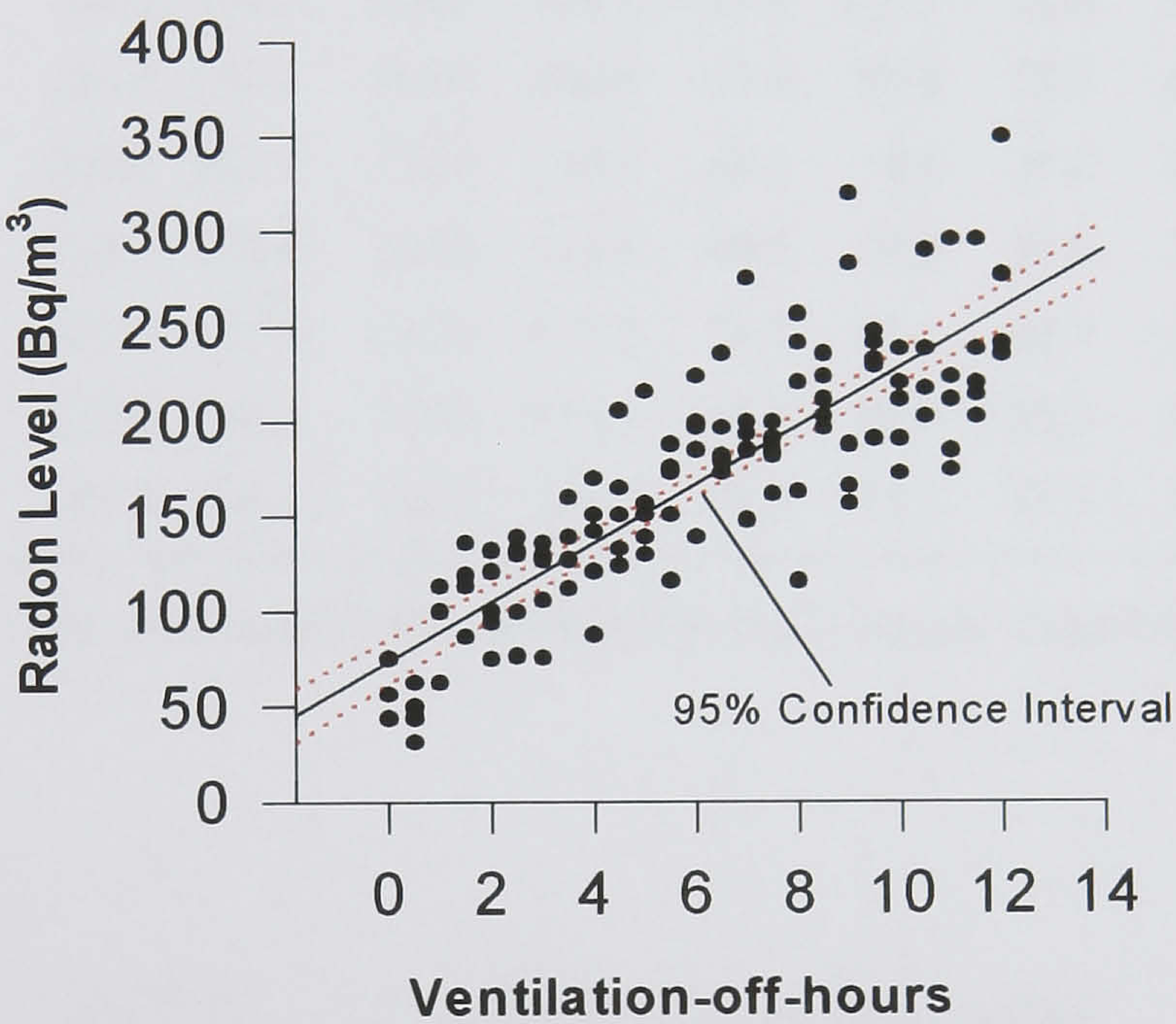


Fig 3-3 Regression for All Periods

However, at t =12 (hours), the radon concentrations became $C_{(12\,hrs)} = 260.61$ (Bq/m^3)

Ventilation-on-hours

The results of these experiments are summarised in *Table 3-1* and *Fig 3-4*. More details are given in the *EngD Portfolio Submission 3*.

V-on-hours	*N=0.30*		*N=0.52*		*N=1.12*		*N=2.08*		*N=4.22*	
	(r=0.79)		*(r=0.87)*		*(r=0.95)*		*(r=0.97)*		*(r=0.99)*	
	M	*C*	*M*	*C*	*M*	*C*	*M*	*C*	*M*	*C*
0.0	351.0	351.0	278.0	278.0	242.0	242.0	236.0	236.0	242.0	242.0
0.5	297.0	328.4	185.0	246.4	185.0	191.8	112.0	158.3	170.0	160.0
1.0	263.0	307.8	263.0	219.5	191.0	154.1	124.0	110.1	112.0	109.9
1.5	251.0	289.1	179.0	196.5	121.0	125.9	90.0	80.1	81.6	79.1
2.0	324.0	271.9	170.0	176.8	124.0	104.7	63.0	61.5	66.5	60.3
2.5	288.0	256.3	148.0	160.0	54.4	88.8	57.0	49.9	39.3	48.7
3.0	200.0	242.0	130.0	133.4	69.5	76.9	39.0	42.7	39.3	41.6
3.5	218.0	228.9	124.0	122.9	60.5	67.9	54.0	38.2	39.3	37.2
4.0	227.0	217.0	157.0	122.9	84.7	61.1	33.3	35.3	15.1	34.5
4.5	239.0	206.1	133.0	113.9	45.4	56.0	33.3	33.5	36.3	32.8
5.0	185.0	196.1	103.0	106.2	42.3	52.2	33.3	32.4	15.1	31.8

Table 3-1 The Measured (M) and Calculated (C) Radon Concentrations at HKUST

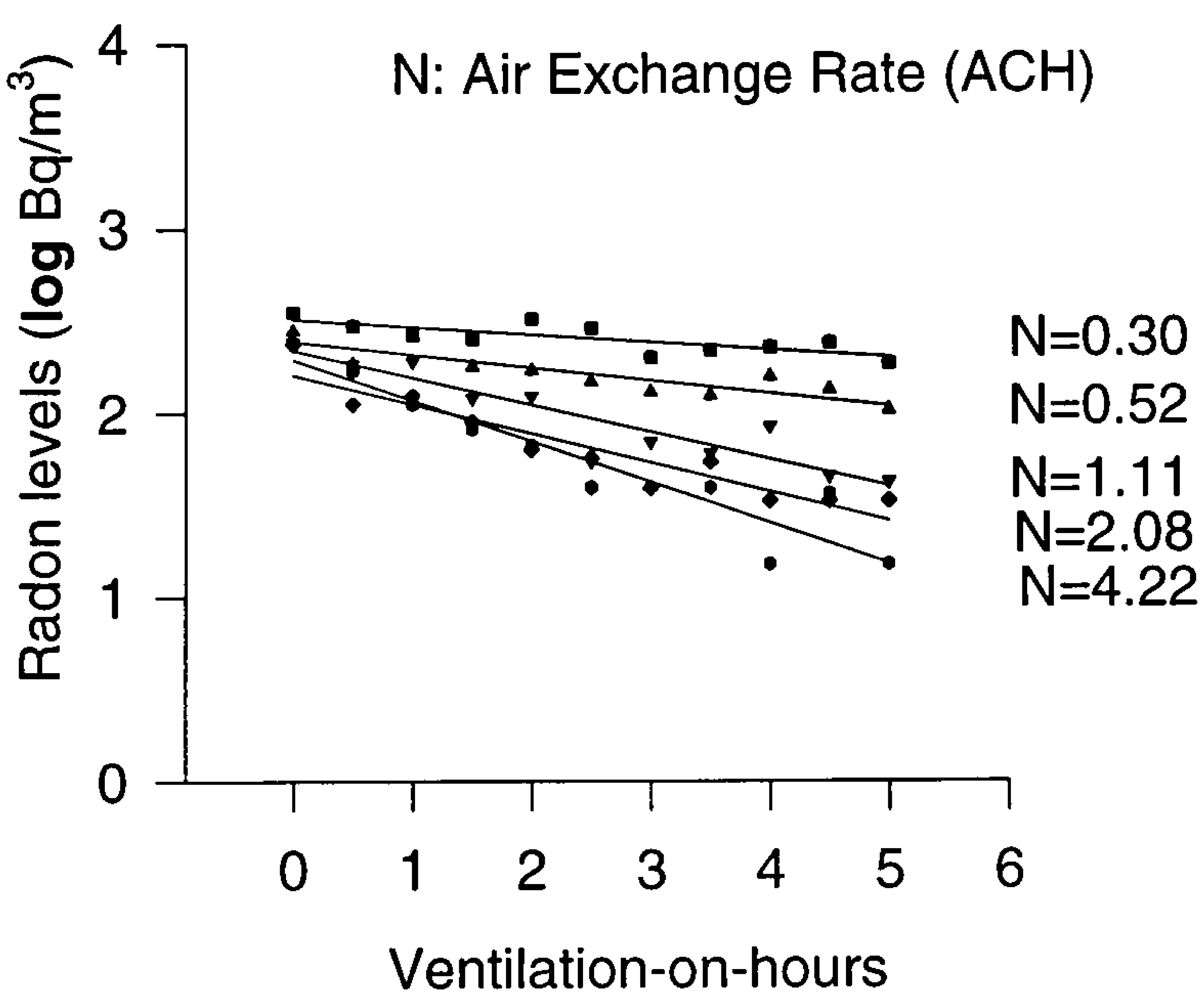


Fig 3-4 The Measured Data for All Experiments

3.5 DISCUSSION

Room Chamber Condition during Ventilation-off-hours

During the period when the HVAC was switched off at night, air exchange rate, N was negligible due to no mechanical ventilation. However, there was a slight natural draft in the room chamber. This slight natural ventilation together with the fact that radon will decay (half-life = 3.8 days) should ultimately cause the accumulated radon concentration to plateau out over time. In our study, the accumulated radon concentration appeared to vary linearly with time. The effect of the natural draft was not observable during the 12 ventilation-off-hours' time period of our study.

Sources of Radon Emissions

The radon emission rate, R, is also an essential parameter of sources in *radon level predictive models.* Without it, the indoor radon concentrations cannot be properly identified. Some notes are made:

1. R can be computed using *model (4)* with data $C_{(t)}$ and t obtained in the experiments previously-mentioned during ventilation-off-hours.
2. R can be used in the *models* for predicting indoor radon concentrations since:
   (a) R reflects the radon emissions given off from building materials into the room chamber. Thus, R is a function of radon emissions given off from building materials, and
   (b) R reflects radon emissions given off from surrounding soil through walls into the room chamber. Thus, R is a function of radon emissions given off from surrounding soil.

Both emissions are the main sources of indoor radon. Both factors (a) and (b) above can be significant sources. For ground floor locations in the multi-storey buildings, factor (a) is more significant.

Indoor Sink Effect

In some cases, indoor surfaces can act as sinks by adsorbing and later remitting vapour-phase organic indoor air pollutants[33]. Indoor sinks play a major role in determining the concentration-versus-time history associated with indoor pollutant sources. They can include wet sources. Indoor sinks of interest include floors, walls, ceilings, HVAC systems and furnishings etc[34]. By adopting this concept of thinking from other IAQ researches, sinks can also interact with radon emission sources to affect radon concentration. Therefore, it is important to identify such interaction. In our study, when not considering the sink effect, as presented in *Fig 3-4,* the data did not show good correlation. However, when the sink effect was considered, as illustrated in the following discussion, the data fit well. To include the indoor sink, a modification factor (M) was then developed and applied into *model (7).* It becomes *(8)* as indicated below:

$$C_{(t)} = \frac{RL}{MN - k}[\exp(-kt)-\exp(-MNt)]+(C_{o'}-C_{in})\exp(-MNt) + C_{in} \qquad (8)$$

where

$C_{(t)}$ is indoor radon concentration as a function of time (mg/m^3)

R is 8.60 $Bq/m^2/hr$ (radon emission rate from room chamber surfaces)

L is 1.81 m^2/m^3 (loading factor), L = S/V

N is 0.30, 0.52, 1.11, 2.08 and 4.22 /hr (air exchange rate)

k is 0.01 /hr (radon decay rate)[35]

t is 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 hr (vent-on-hours)

$C_{o'}$ is 351 (N = 0.30), 278 (N = 0.52), 242 (N = 1.11), 236 (N = 2.08) and 242 (N = 4.29) Bq/m^3 (initial room concentration of radon)

C_{in} is 15 Bq/m^3 (background radon concentration in fresh air)

M is the modification factor.

By using the regression function of the PC simulator[36], M was identified. The associated simulation programme is shown in the *EngD Portfolio Submission 3:*

Parameter	*Value*	*StdErr*	*CV(%)*	*Dependencies*
Z	*1.869e-1*	*1.855e-2*	*9.927e+0*	*0.0000000*

N (1/hr)	*MN (1/hr)*	*M=(MN/N)*
0.3031	0.1869	0.6166
0.5178	0.3187	0.6155
1.1147	0.5779	0.5184
2.0819	0.9545	0.4585
4.2229	0.9824	0.2326

Where, for simulation, $Z = MN$

Table 3-2 The calculation for Modified Factor (M)

Fig 3-5 shows the curve fitting results using the *model (8)* after the inclusion of modification factors.

The curves fit the experimental data extremely well. Analysis for the curves was undertaken throughout the verification process.

To further validate the *model*, a linear relationship between the air exchange rate (N) and the modification factors (M) was observed. The *model* for this linear regression is:

$M = 0.6507 - 0.0985 * N$

Or $M = 0.65 - 0.1N$ ($r^2=0.99$, $p<0.01$) *(9)*

Using mathematical *model (9)*, it becomes convenient to compute the values of the

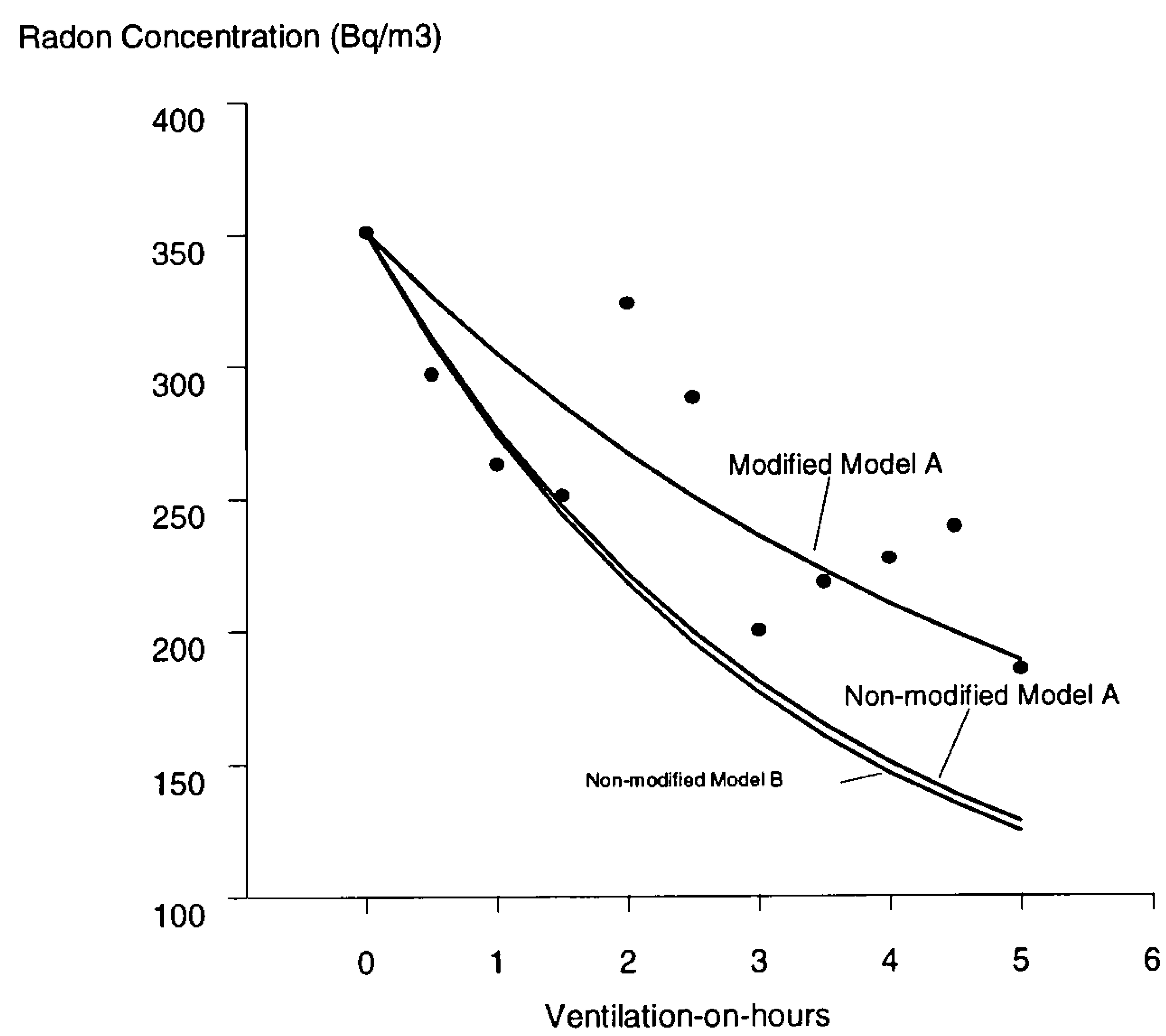


Fig 3-5 Comparing modified & non-modified models (when N=0.30 ACH)

modification factors with different air exchange rates varying between 0.25 ACH and 4.0 ACH. Details are given in the *EngD Portfolio Submission 3.*

Fig 3-6 shows the modified ventilation-on-hours patterns for characterising indoor radon concentrations. For different air exchange rates with the same initial indoor radon concentration ($C_{o'}$ = 260 Bq/m^3), the following results were found: When N = 1.0, it takes only half an hour for $C_{(t)}$ to arrive at 208 Bq/m^3; When N = 0.5, then it takes one hour for the $C_{(t)}$ to arrive at 210 Bq/m3. Both of these levels are very close to the WHO recommended action level of 200 Bq/m^3.

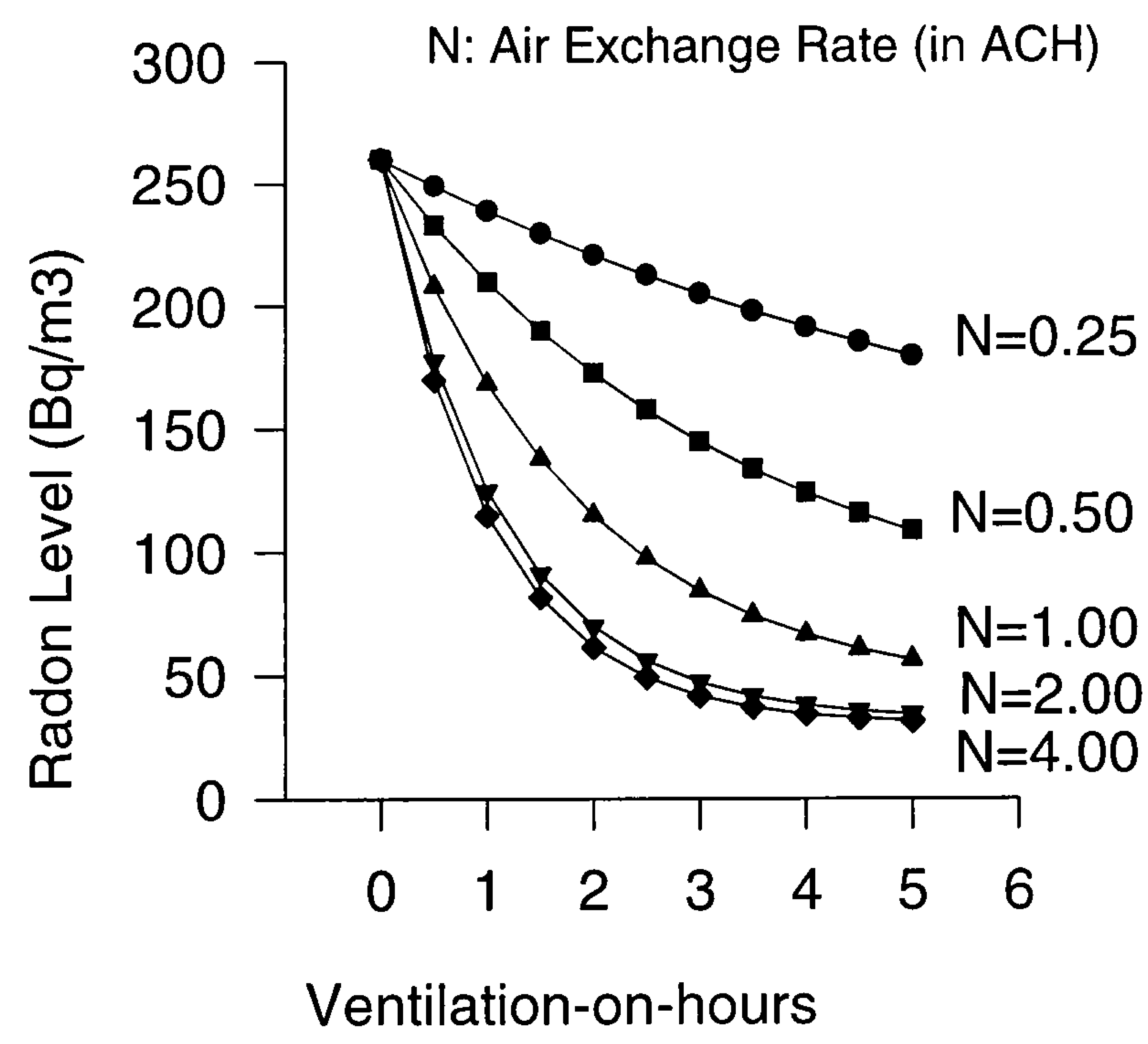


Fig 3-6 The Calculated Data of All Experiments

Verification of the Derived *Predictive Models*

1. Ventilation-off-hours *Model*

Using our previously-derived modified *model* for ventilation-off-hours, $C_{(t)} = C_o + Rlt$, we find that $C_{(12hrs)}$ = 73.82 (Bq/m^3) +8.60 (Bq/m^2/hr)*1.81(m^2/m^3)*12 (hrs) = 260.62 (Bq/m^3). That is very close to the identified average peak result[16],[18],[20] of 264 Bq/m^3 in

Chapter 2. Assuming the average ventilation-off-hours at HKUST is 12 hours, *the radon level predictive model* developed can be confirmed to be representative of the HVAC environment in HKUST.

2. Ventilation-on-hours *Model*

The *model* was successfully verified during experiments in which the N parameter was varied. The observed results matched one another as demonstrated in *Table 3-1.* The *model* was further verified by varying the R parameters, from 8.60 to 4.85 Bq/m^3. In the room chamber studies as to be presented in Chapters 4 and 5, the evaluation of different Polyurethane-based surface covering effects on preventing radon emission from walls will be involved. *Fig 3-7* shows the results of a coated room which provides evidence that the modified *radon level predictive model* with the same modification factor is capable of matching the data well[18]. Details are provided in the *EngD Portfolio Submissions 3 and 4.*

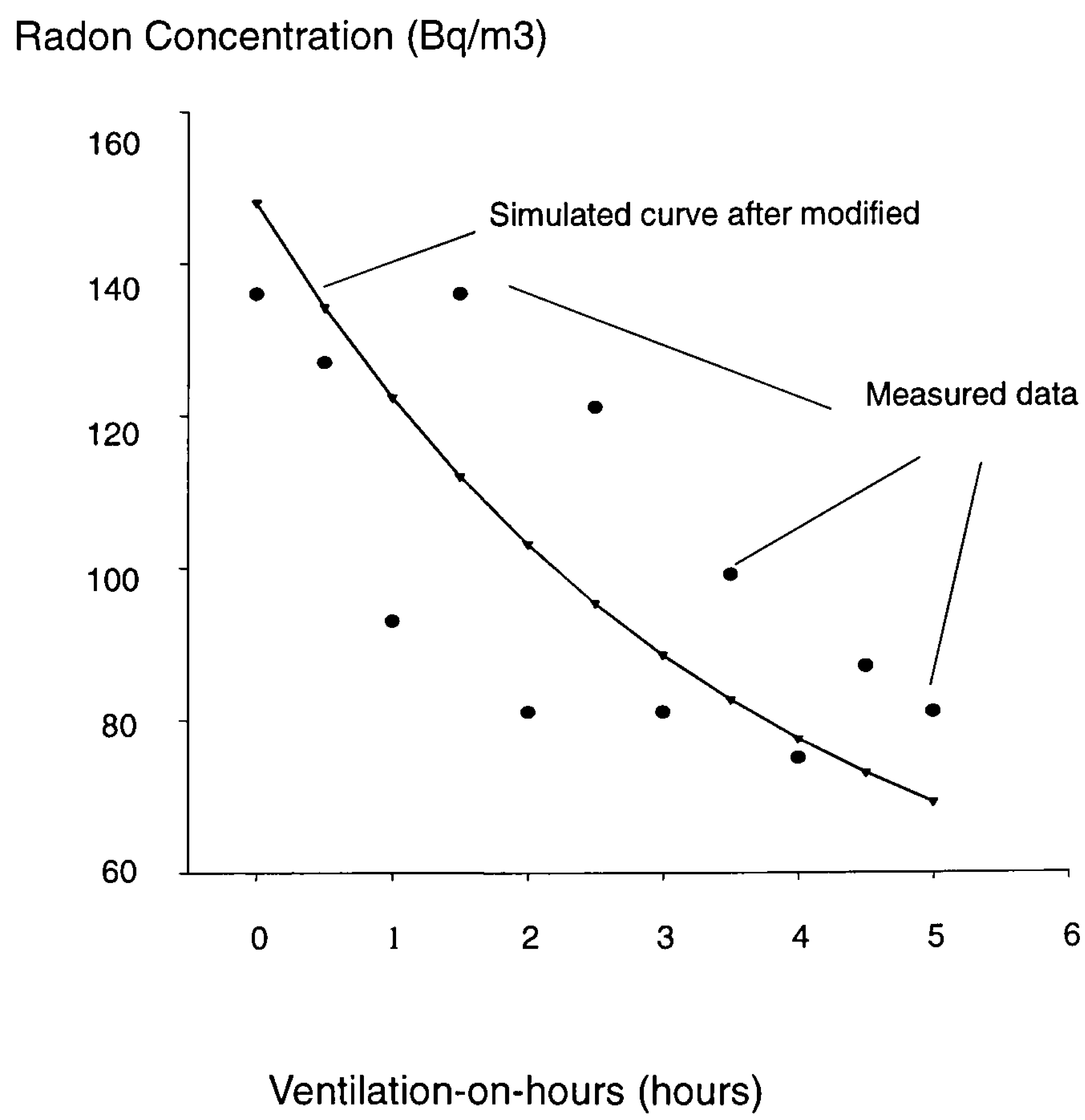


Fig 3-7 Results of a P-u coated Room with N=0.48 ACH; M=0.60

3.6 CONCLUSIONS

This set of experiments yield the following conclusions:

1. Indoor radon levels were found to increase linearly with time during the period when the HVAC system was switched off and to decrease exponentially after the system was resumed. A *model* was formulated to successfully predict radon concentrations;

2. With the inclusion of a modification factor to account for the radon sink effect, a pre-existing VOC concentration predictive model can be successfully used to predict indoor radon concentrations; and

3. The derived *radon level predictive model* correlates well with the field measured data verified by varying the air exchange and radon transmission rates of the HVAC environment.

Chapter 4

ACTIVE & PASSIVE RADON CONTROL

4.1 AN OVERVIEW

This Chapter describes the *Active* and *Passive Radon Control Approaches* in a heating, ventilating and air-conditioning (HVAC) environment. By applying our previously-derived *radon level predictive models* in Chapters 2 and 3 with specific modification factors, radon concentrations under different conditions of HVAC operations can be accurately estimated. The effects of various combinations of these schemes were also tested mathematically.

Many possible combinations demonstrate desirable effects. Examples include maintaining a minimal air exchange rate without operating the full HVAC systems during the off work hours. And, the early actuation of the HVAC system at the beginning of the workday together with the early shut down of the system towards the end of the regular workday, etc.

A thorough energy analysis has been conducted and the hourly cost per unit air-conditioned space has been defined prior to this part of the study. The challenges for this management study are:

- To execute an *Active Radon Control Approach* through a Cost-effective design of the HVAC operating schedule to enable the management of indoor radon concentrations along with high energy efficiency; and

- To execute a *Passive Radon Control Approach* through the application of Polyurethane-based (P-u) paints as internal wall and floor covering to enable the management of indoor radon concentrations with reduced energy demand.

4.2 *ACTIVE RADON CONTROL APPROACH*

A Brief Overview of the *Active Radon Control Approach*

The *Active Control Approach* to reduce indoor radon concentrations can be generally summarised into three major categories[37],[38]:

- Use of Ventilation and Outdoor Air;
- Air Cleaning; and
- Removal of Radon from Water.

This section presents the feasibility study on the *Active Radon Control Approach*, "Use of Ventilation and Outdoor Air" with a goal of managing indoor radon concentrations of a HVAC serviced environment in a energy-efficient manner. This is to be carried out through the design of an "Energy-efficient HVAC Operation Schedule" to address the indoor radon concentration issue.

HKUST Campus Environment serviced by HVAC system

The Hong Kong University of Science and Technology (HKUST) is a public-funded institution opened in 1991 and has a population of approximately 7,000 full-time students and 3,000 staff. Situated on a steep slope beside the shore, the campus grounds are terraced to provide buildings on all levels. It has an unobstructed view of the sea at the northern end of Clear Water Bay Peninsula in Hong Kong.

The University's 60 hectares include around 0.3 Million square metres of gross floor space for offices, classrooms, laboratories, student and staff accommodations. Half of this 0.3 Million square metres are fully serviced by a computerised HVAC system, one of the largest and most sophisticated HVAC systems in Hong Kong. The system includes 201 AHU, 3,594 FCU and a central chiller plant with a huge capacity of 7,000 Tons of Refrigeration. HKUST consumes an enormous amount of energy for the HVAC system costing in the amount of approximately 20 Million Hong Kong Dollars a year. However, at the same time, the ten thousand staff and students who occupy these areas are potentially affected by indoor radon.

Operating Condition of the HVAC System at HKUST

A complete energy analysis was conducted to assess the consumption pattern of the HVAC plant of the HKUST campus between the period of Week 14, 1995 and Week 4, 1998. Details are given in the *EngD Portfolio Submission 4*. During the aforementioned period, the total electricity consumption of the HVAC plant of HKUST was 51,661,899 kilowatt hours (KWh). The average cooling capacity of the HVAC system per each kilowatt of electricity supply in HKUST was thus calculated as 0.91 TR (Tons of Refrigeration). This is equivalent to 0.26 kilowatt of cooling capacity (as 1 KW = 3.52 Tons). In other words, it required around 1.11 KW of electricity to generate 1 TR (1.11 KW/TR). This is an essential parameter for evaluating the cost-effectiveness of each *Radon Control Approach* in the later sections.

Study on *Active Radon Control Approach* using Cost-effective HVAC Scheduling

Models (4) and *(8)* derived from Roache et al., Guo et al. and Lawless et al., but modified as per Chapter 3, are used:

During the OFF time of HVAC System:

$$C_{(t)} = C_o + RLt \qquad (4)$$

During the ON time of the HVAC System:

$$C_{(t)} = \frac{RL}{MN - k}[\exp(-kt)-\exp(-MNt)]+(C_o-C_{in})\exp(-MNt) + C_{in} \qquad (8)$$

Model (4) was used to compute R, the radon emission rate from the internal room chamber surfaces. As this *model (4)* correlates well with the experimental data as taken from Chapter 3, R can be determined by b/L or 15.57/1.81 or 8.60 Bq/m^2/hr. During the HVAC "off" period, t = 12 hours, then $C_{(t)}$ = 260 Bq/m^3, the value was also found to be extremely close to the result in the *EngD Portfolio Submission 2*, which was C_{peak} = 264 Bq/m^3.

Model (8) was used to account for the effects of different variables during the HVAC system "on" period, with a modification factor, M = 0.65 - 0.1N as derived in Chapter 3. After applying this modification factor, *model (8)* also correlates well with the experimental data.

Where:

Parameters	*Description of items and Indicators*	*Value*	*Units*
C_o	Initial radon concentration in experimental room chamber	31.22	Bq/m^3
$C_{o'}$	Peak radon concentration in room chamber	260	Bq/m^3
N	Fresh air exchange rate of the room, N=A/V	1.0	ACH, /hr
M	Modification factor due to sink effect of room (M=0.65-0.1N)	0.55	/hr
k	Source decay rate[35]	0.01	/hr
R	Radon emission rate from room chamber surfaces	8.6	Bq/m^2-hr
L	Loading factor of room chamber , L = S/V	1.81	m^2/m^3,
	S = Surface area of room chamber selected for experiment		/m
	V = Volume of above experimental room chamber		
t	Elapsed time (variable) taken during the experiment	-	hr
$C_{(t)}$	Cumulative radon concentration emitted from walls at time t	-	Bq/m^3
C_{in}	Background radon concentration in fresh air	-	Bq/m^3
A	fresh air volume per hour, A = 3600 U*F;	-	m^3/hr
	U = Flow velocity of HVAC inlet (m/sec);		
	F = Cross sectional area of above inlet ducting (m^2)		

Full details are given in the *EngD Portfolio Submission 3*, Chapter 3 of this Executive Summary and some recently published papers of Chan et al.[16]-[21].

Results of an *Active Radon Control Approach* using Cost-effective HVAC Scheduling

Table 4-1 and Fig 4-1 show the results of radon concentrations from computation, using the SigmaPlot Software[36] as indicated in previous chapters. Six different modes of AHU Operation scheduling are provided for comparison. Where,

- "Now" refers to present Operation Schedule being used in HKUST
- Vent-on-time refers to the starting time of outdoor air intake in HVAC system
- Vent-off-time refers to the termination time of the outdoor air intake in HVAC system
- Vent-on-hrs refers to "on" period of outdoor air intake in HVAC system

Operational Schedules of AHU	*Vent-off-time*	*Vent-on-time*	*Vent-off-hours*	*$C_{(Vent\text{-}on\text{-}time)}$ in Bq/m^3*	*Hours-before-9:00*	*$C_{(9:00)}$ in Bq/m^3*	*Vent-on-hours*	*Daily AHU Operational cost (HK$)*
"Now"	21:00	9:00	12	260.6	0	260.6	12	480
1	1:00	9:00	8	198.3	0	198.3	16	640
2	21:00	8:30	11.5	252.8	0.5	202.4	12.5	500
3	20:00	8:24	12.4	266.8	0.6	203.9	11.6	464
4	19:00	8:18	13.3	280.8	0.7	204.9	10.7	428
5	18:00	8:06	14.1	293.3	0.9	195.6	9.9	396

Table 4-1 Result of *Active Control Approach* using Cost-effective Scheduling of AHU operations to manage Indoor Radon Concentrations at HKUST

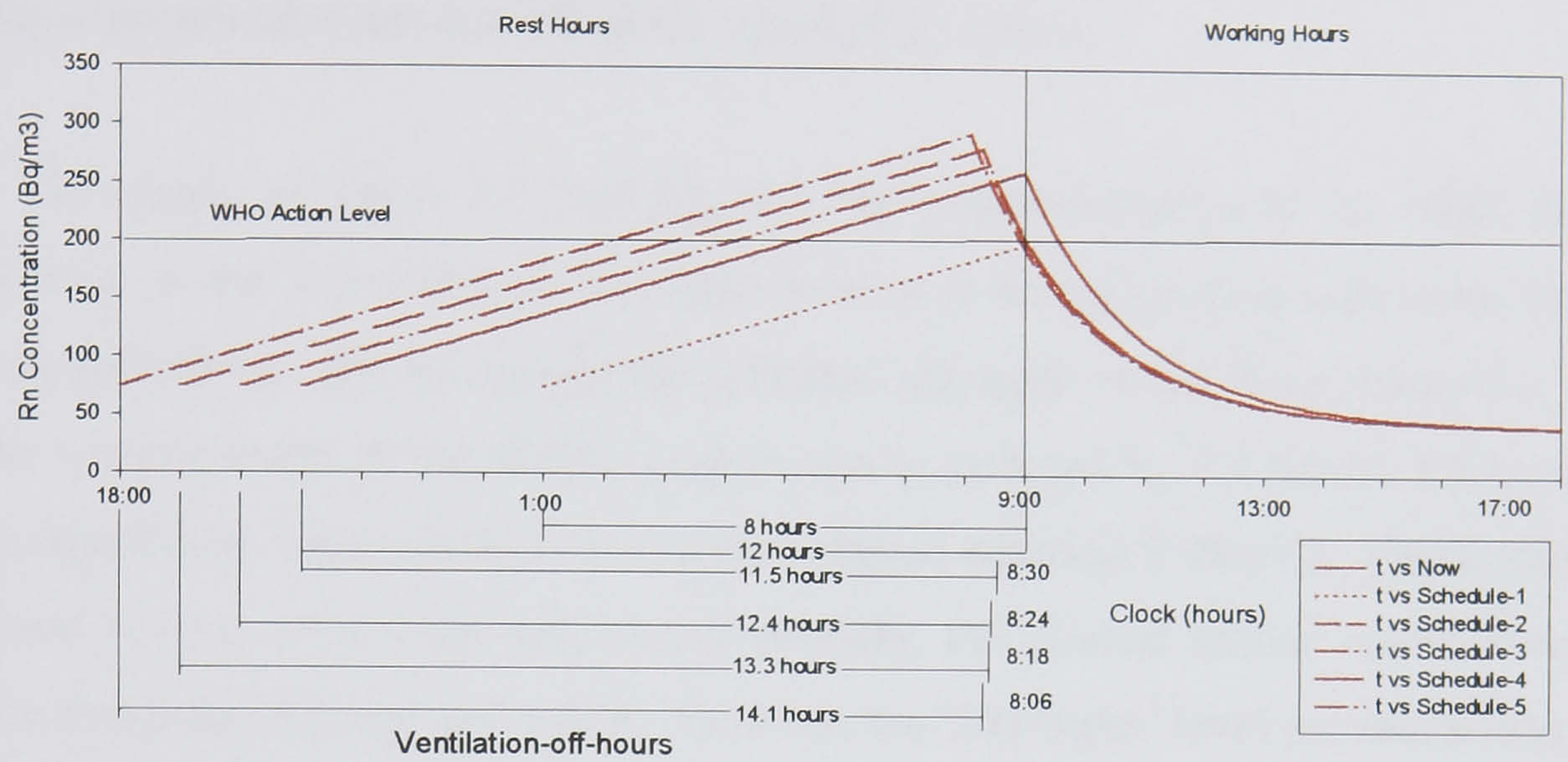


Fig 4-1 Result of *Active Control Approach* using Cost-effective Scheduling of AHU operations to manage Indoor Radon Concentrations at HKUST

- Vent-off-hrs refers to the "off" period of the outdoor air intake in HVAC system
- $C_{(Vent\text{-}on\text{-}time)}$ refers to the radon concentration in Bq/m^3 at Vent-on-time
- $C_{(9:00)}$ refers to the indoor radon concentration in Bq/m^3 at 9:00 am
- Hours-before-9:00 refers to the total hours of ventilation termination before 9:am

Table 4-1 and Fig 4-1 show a comparison of 6 different operational strategies of the AHU system. The "Now" mode is the existing operational schedule for most of the HVAC system at HKUST whereas the operational modes from numbers 1 to 5 are designed to meet the WHO's 200 Bq/m^3 guideline for acceptable indoor radon concentrations. It is of particular importance to achieve this WHO level by the beginning of the normal office hour, 9:00 in the morning, when most students and staff make their entry to the HVAC indoor environment of HKUST.

It is important that a good indoor air quality (IAQ) environment for the HKUST community can be ensured. Emphasis has to be put at the beginning of each day after a long night of indoor radon accumulation due to the radon emission characteristics of the HKUST building materials and the shut-off of the ventilation system.

As shown in *Table 4-1 and Fig 4-1*, the implementation of the AHU Operational Schedules 3, 4 and 5 provides a cost-effective way to control indoor radon concentrations at an acceptable level. By reviewing the operation duration of the three schedules, it appears that the running hours of the HVAC system can be reduced by 0.4 hours, 1.3 hours and 2.1 hours respectively, when compared with the original schedule ("Now"). These results would give good savings of energy and, simultaneously, the desired indoor radon concentrations could be maintained properly by 9:00. This was the 200 Bq/m^3 level recommended by WHO as reviewed in the *EngD portfolio submission 1.*

4.3 *PASSIVE RADON CONTROL APPROACH*

A Brief Overview of the *Passive Radon Control Approach*

The *Passive Control Approach* for reducing indoor radon levels can be generally summarised into four major categories[37],[38]:

- Active and Passive Soil Depressurisation;
- Sealing;
- Building Pressure Control; and
- Source Removal.

These approaches are effective ways of improving the indoor air quality (IAQ) of a building environment by effectively preventing air pollutants from gaining entry. In this Chapter, major materials for the construction of the building structure of HKUST had been tested preliminarily for their radon emission characteristics as a pilot study for a *Passive Radon Control Approach.* The study was carried out by means of a climate chamber designed by the IAQ Laboratory of the Hong Kong Polytechnic University.

To further study the *Passive Control Approach*, an experimental chamber serviced by the HVAC system was also identified at HKUST. This involved the investigation of the effectiveness of surface treatments as a barrier to the radon emission. Finally, a financial assessment was carried out to identify the actual energy savings in applying this *Passive Radon Control Approach.*

Climate Chamber Pilot Study: Characterising Building Materials as radon sources

1. A Brief Description of the Experimental Climate Chamber

A small 32cm x 21cm x 20cm (13.44 cm^3 in volume) PVC climate chamber was made by the Indoor Air Quality Laboratory, Hong Kong Polytechnic University for radon studies. The chamber was fitted with a small electrical fan to provide forced air circulation (DC 12 Volts). Radon generated from test materials placed in the chamber was contained and measured. *Fig 4-2* shows the set up of the building material tests.

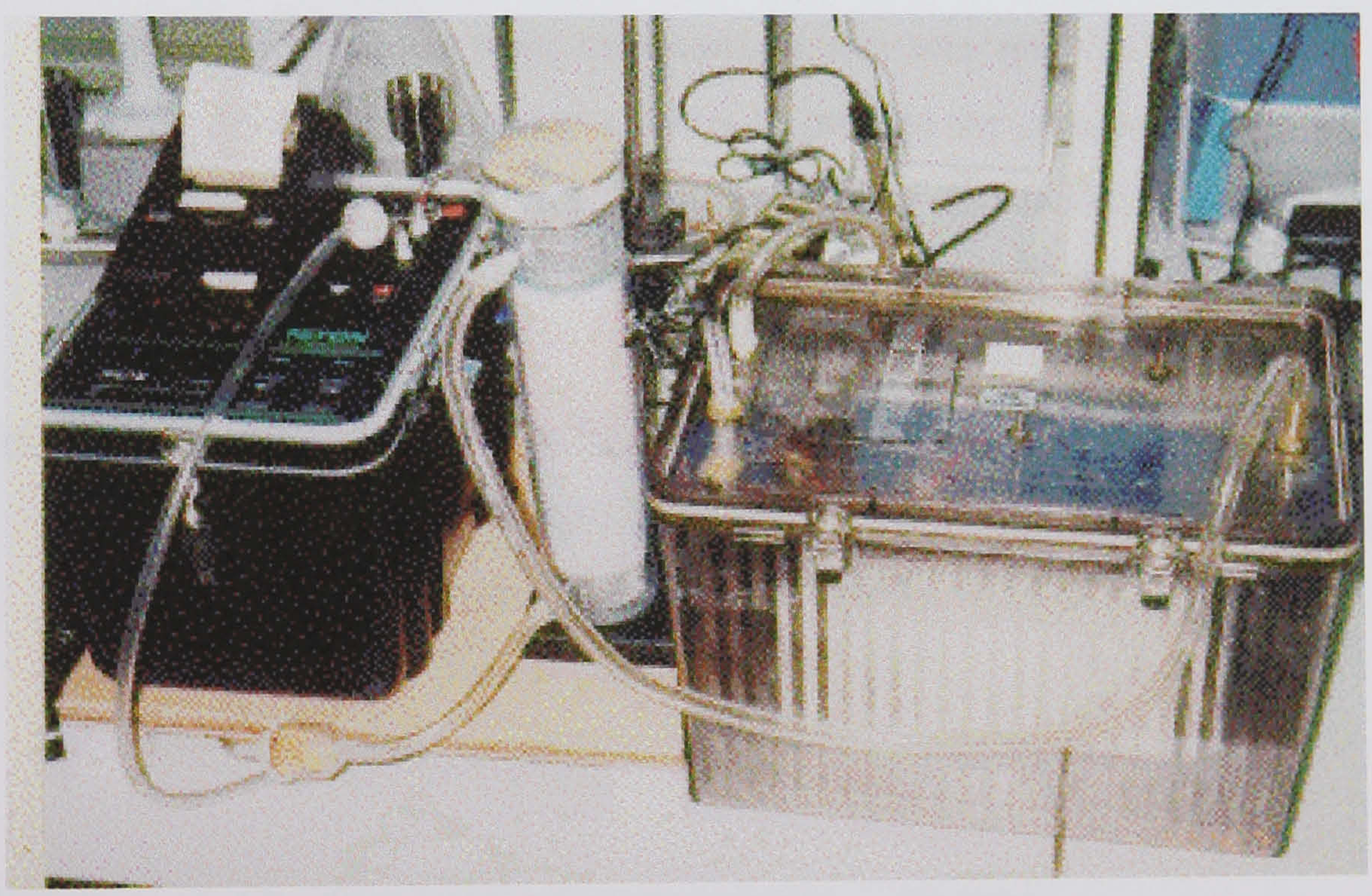


Fig 4-2 Testing of HKUST building materials using climate chamber and RAD-7 Continuous Radon Gas Monitor

2. Testing of Different Building Materials Used in HKUST Campus

The building materials tested include:

(1) a Unpainted clay brick (22cm x 9.5cm x 7cm),

(2) a gypsum board (20cm x 9.5cm x 5cm), and

(3) a cement brick (14.5cm x 15cm x 10cm)

More details are given in the *EngD Portfolio Submission 4.*

3. Different Surface Treatments Applied on HKUST Building Brick Material

The radon emission treatments for the nude clay brick included:

Step 1. Unpainted clay brick without treatment,

Step 2. Same brick treated with water-based limestone paint, and

Step 3. Same brick treated with a layer of P-u paint.

Preparation work for the test materials of the experiment was performed inside a fume cupboard, which was used to contain and exhaust unpleasant odours or toxic vapours to prevent the contaminants being trapped inside the HVAC serviced environment of the laboratory building of the university. More details are given in the *EngD Portfolio Submission 4.*

4. Investigated Items and Indicators for the Climate Chamber pilot study

$C_{(t)}$: Radon concentration in climate chamber during experiment (Bq/m^3);

t: Elapsed time during experiments (hr);

T: Air temperature in chamber (^oC); and

H: Air humidity in chamber (%).

5. Measurement of Radon Concentrations and Other Indicators

The measuring instrument for radon concentrations inside the climate chamber was the time-integrated continuous monitoring device known as "RAD7 professional continuous radon gas monitor (RAD7)" made by the Niton Corporation in the United States of America (USA). Measurement frequency is 30 minutes a cycle, 48 cycles a day. Temperature and humidity were monitored using an RS 212-540 Model Thermo-hygrometer.

6. Results of Experimental Studies using the Climate Chamber

a. Radon Emissions after applying Different Coverings on HKUST Building Material Surfaces

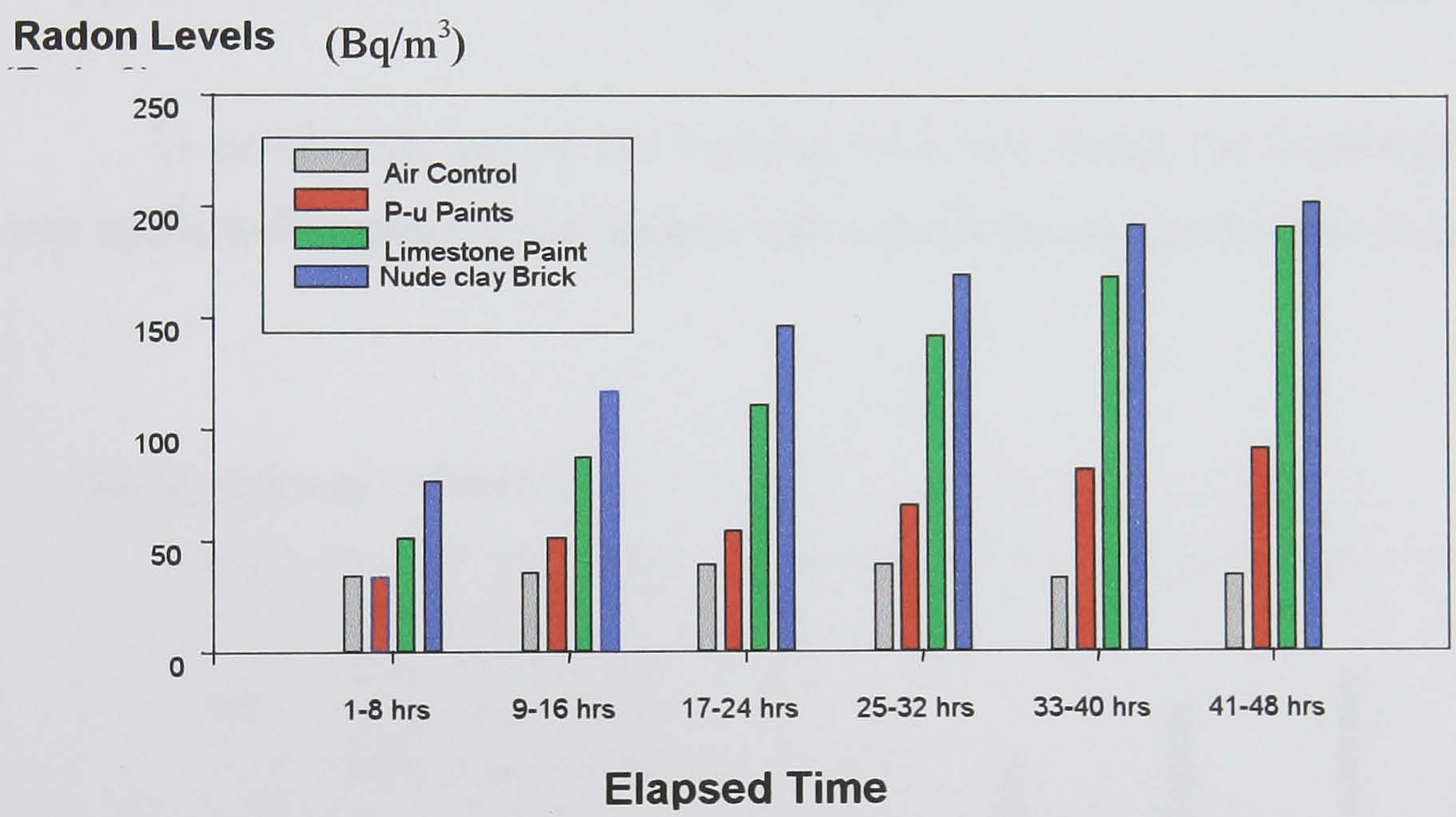


Fig 4-3 Climate Chamber Study for Surface Coverings

Fig 4-3 shows the radon concentrations (Bq/m^3) from the building materials after application of different surface coverings. More details are given in the *EngD Portfolio Submission 4.* To summarise, the measured radon emission levels in decreasing order were as follows:

Unpainted clay Brick > Water-based Limestone Paint applied on Brick > Polyurethane-based paint on same brick with water-based limestone paint > Air Control ($p<0.01$).

The climate chamber pilot study indicated the potential for reducing the radon emission rate from the unpainted clay brick by up to 50% after the application of limestone water based paint followed by P-u paint.

b. Radon Emission Capability for Different Types of HKUST Building Materials Used

Fig 4-4 presents the results of the radon emission from different building materials taken from the HKUST campus. The radon levels emitted from different materials placed into the chamber were observed with the following decreasing order:

Unpainted clay Brick > Cement Brick > Gypsum Board > Air Control ($p<0.01$).

In conclusion, among the building materials tested, the unpainted clay brick was confirmed to generate the highest radon levels among the test materials.

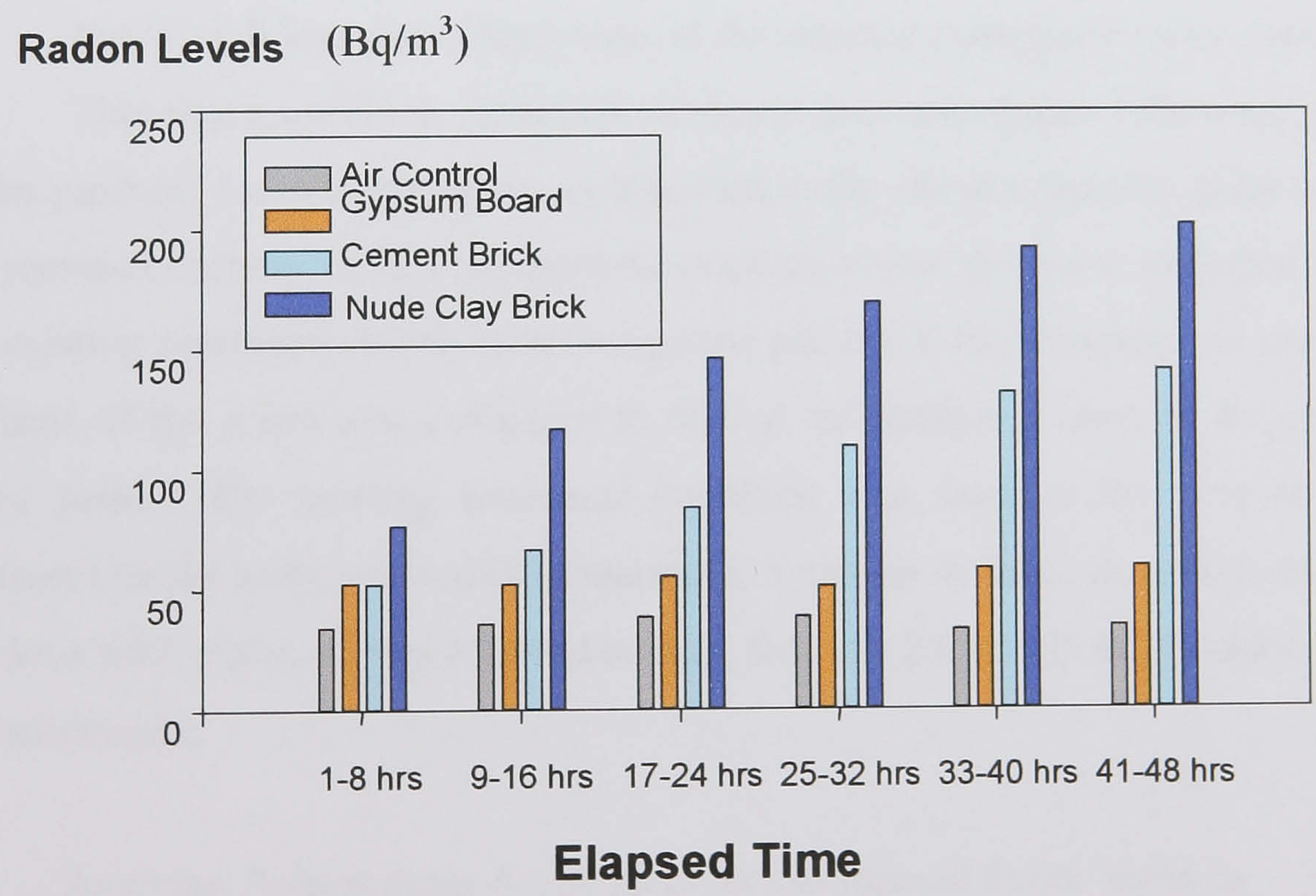


Fig 4-4 Climate Chamber Study for Building Materials

Room Chamber Study on *Passive Control Approach* by Sealing Radon Entry Sources

1. Room Chamber Selected for Experimental studies

   Same as in Chapter 3.

2. Investigated Items and Indicators for the Room Chamber Studies

   Same as in Chapter 3.

3. Measurements of Indoor Radon Concentrations for Room Chamber Studies

   Same as in Chapter 3.

4. Measurement of Other Indicators for Room Chamber Studies

   Same as in Chapter 3.

5. Radon Source Elimination after applying Different internal surface coverings

a. Applying Water-based limestone on the internal surfaces of room chamber

This radon emission reduction treatment was undertaken following the order of the previous set of experiments as indicated in the climate chamber pilot studies of the previous section. It is a comparison exercise, where the radon emission effect of the existing condition (water-based limestone paints) of the treatment on the internal surfaces of the room was compared to that of an additional layer of Polyurethane-based paint. The existing limestone condition was used as the first or original treatment on the room's or building materials' emission surfaces as compared with the previous pilot study. N was adjusted to 0.25, 0.5, 1.0, 2.0 or 4.0 ACH respectively for measurements;

b. Applying Polyurethane-based paint on the internal Room Surfaces

As confirmed by the results of the previous climate chamber pilot studies, Polyurethane-based paints applied on water-based limestone treated building material surfaces can reduce its radon emissions. In order to reflect this successful effect into a real room environment, in this experiment, one layer of P-u paint was applied on the internal room surfaces as the second treatment, followed by another layer of P-u paint as the third treatment. N was also adjusted to 0.5 or 1.0 alternatively.

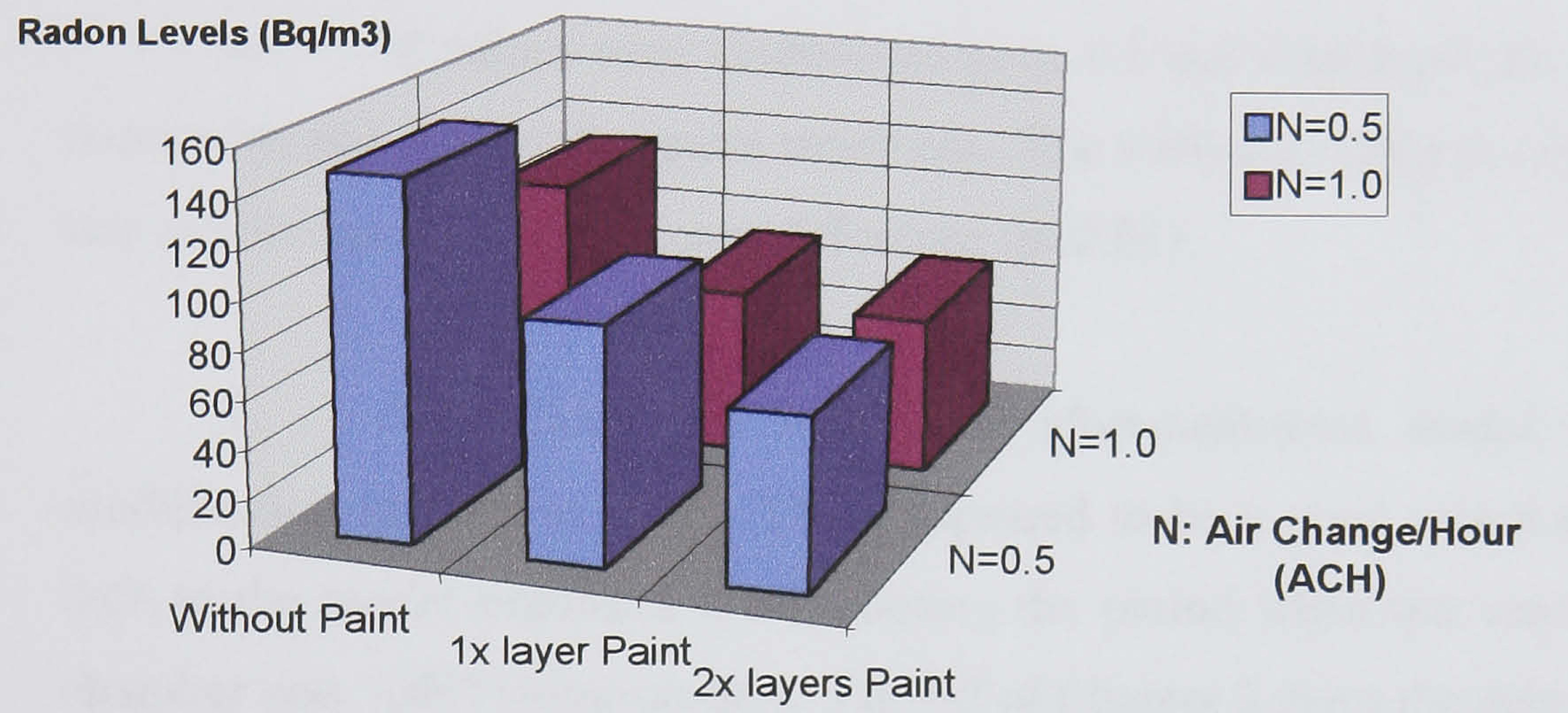


Fig 4-5 Daily Average Radon Levels in Room Chamber without painting, with 1 or 2 layers of P-u paint applied on the internal room surfaces

6. <u>Result of Room Chamber Studies to confirm the *Passive Radon Control Approach*</u>

a. *Fig 4-5* presents the effect of wall coverings on radon emission in a room chamber environment after the respective treatment of one and two layers of P-u paints over water-based limestone paint. Most data are provided in the *EngD Portfolio Submission 4* with some background data extracted from the *EngD Portfolio Submission 3*. The results of radon emission from the internal surfaces with and without P-u paint are also shown. It was observed that the radon concentrations of the room chamber was lowest after the walls and floor surfaces were coated with a second layer of P-u paint as the third treatment. This effect existed in both room situations with air exchange rates adjusted to 0.5 and 1.0 ACH.

b. With the same method as introduced in Chapter 3, the radon emission rate, R from the internal surfaces of the room chamber (those ceiling, floor and walls) was determined after being covered by the Polyurethane-based paints. As shown in the *EngD Portfolio Submission 3,* the regression model was found in good correlation[36] with the experimental data obtained ($r = 0.7592$, $p<0.01$). Using this linear regression relationship, $C_o = 31.22$ Bq/m^3, R = 8.77/1.81 or 4.84 Bq/m^2/hr.

a. R values were determined to be 8.6 and 4.84 Bq/m^2/hr respectively for those with and without P-u paint treatment. The statistical analysis confirmed that the two conditions are of significant difference ($p<0.01$).

b. To validate the result, the aforementioned *model* with the same modification factor was used. There appeared to be a good match of experimental data to the *model*-simulated results during the period when the ventilation of room chamber was "ON" (Vent-on-hrs). *Fig 3-7* of Chapter 3 gives the details.

Results on the *Passive Control Approach* of Sealing Indoor Radon Entry Sources

Table 4-2 and Fig 4-6 provide the simulated results of radon concentrations using the SigmaPlot Software[36]. Indoor radon concentrations measured before and after the application of internal surface treatments on the walls and floor of the experimental room chamber were generated for comparison purposes. The abbreviations have been described in previous sections.

Polyurethane –based Painting	*Vent-off-time*	*Vent-on-time*	*Vent-off-hours*	*C(9:00) in Bq/m^3*	*Vent-on-hours*	*Daily AHU Operational cost (HK$)*
Before	21:00	09:00	12	260.6	12	480
After	15:00	09:00	18	189.1	6	240

Table 4-2 Results of *Passive Radon Control* Strategy after using P-u paint applied on the internal Room Surfaces

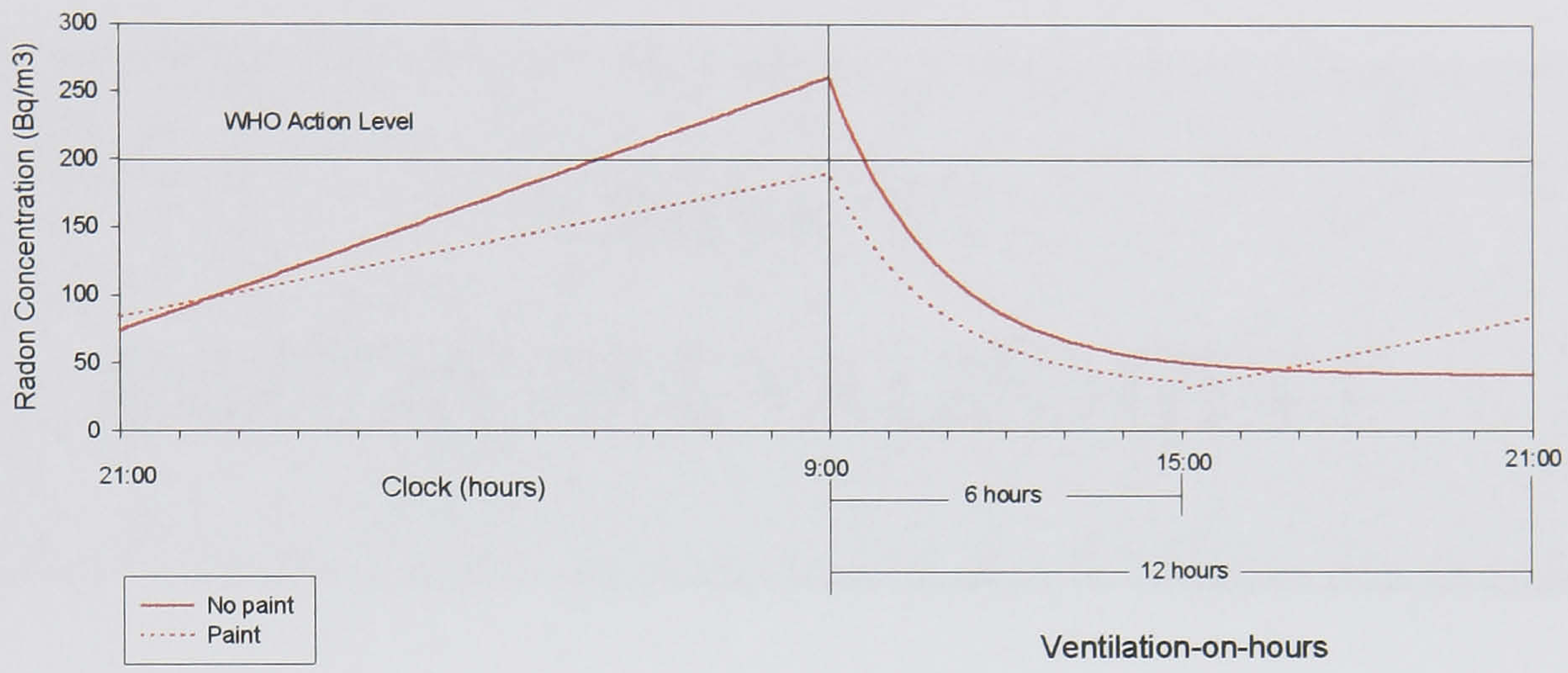


Fig 4-6 Results of *Passive Radon Control* Strategy after using P-u paint applied on the internal Room Surfaces

4.4 CONCLUSIONS

The results of this engineering management study yield the following conclusions:

1. The application of Polyurethane-based paint treatment on all internal room surfaces has a significant effect on reducing radon emission from the surrounding walls and floor in an indoor environment; and

2. An additional layer of P-u paint covering on concrete building material can improve the effectiveness of reducing radon transmission.

Chapter 5
RADON MANAGEMENT

5.1 AN OVERVIEW

This Chapter focuses on mathematical computation to estimate the savings after application of previously-derived energy-efficient management strategies for controlling indoor radon concentrations at the Hong Kong University of Science & Technology. As introduced in Chapter 4 and the recent published papers of Chan et al. [18],[19], the radon management strategies to be utilized in the heating, ventilating and air-conditioning (HVAC) environment like HKUST involve two parts:

- *Active Control Approach* involves reducing radon concentrations after emission of radon into the HVAC environment of HKUST; and
- *Passive Control Approach* involves preventing radon from entering the HVAC environment of HKUST.

The result indicated, after application of an *Active Radon Control Strategy,* yields an energy savings potential of HK$2.7 Millions a year. However, after application of a *Passive Radon Control Strategy* in the HVAC environment of HKUST, radon emission from the surrounding buildings surfaces can be effectively reduced by approximately 50%. The potential energy savings with this *Passive Control strategy* using P-u paint covering becomes HK$5 Million which is double the dollar savings of the *Active Control Strategy.* To implement the latter strategy, it is estimated to require a project investment of approximately HK$ 57 Million with a discounted payback period of 13 years.

5.2 MANAGEMENT STRATEGY USING AN *ACTIVE RADON CONTROL APPROACH*

The *Active Radon Control Approach* using "Cost-effective AHU Primary Air Unit (AHU-PAU) Scheduling" and "Cost-effective AHU Outdoor Air Damper (AHU-OAD) Scheduling" is found to be a successful energy-efficient method to manage indoor radon concentrations in a HVAC environment. The methods and results have been presented in Chapter 4.

Where,

1. The 35 AHU-PAU were designed to draw 100% fresh air from outdoors. The air is then treated and distributed through fresh air ducts to the fan coil unit system of the university; and
2. HKUST has installed 166 AHU-OAD with fresh air being drawn in directly from the outdoors through an individual fresh air duct of the AHU. The OAD are controlled by the Building Management System (BMS) which modulates the fresh air intake volume from outdoors according to the established criteria of the HVAC environment. This system is the largest computerised BMS in Hong Kong and contains approximately 25,000 control and monitoring points.

The evaluation process is shown below:

1. <u>Annual Savings for *Active Radon Control Approach* by 35 AHU-PAU</u>

After analysis of the existing AHU system, 35 air handling units are in PAU function, occupying a total cooling of capacity of 5,763 KW. The additional fan motors are used for air re-circulation of the HVAC system.

To estimate the energy savings for AHU, the following equation has been derived from the *EngD Portfolio Submission 4*:

Energy Savings = (AHU cooling load in KW x 0.26 + Fan Motor KW) x hr-saved

That is, the annual energy savings for each AHU using the operational strategy of Cost-effective PAU scheduling can be estimated by:

Annual Energy Savings = (AHU cooling load in KW x 0.26 + Fan Motor KW) x hr-saved per year

Each year, we estimate (365 – 17 public holidays – 52 Sundays) = 296 days of HVAC operation (assuming most AHU run full day on all Saturdays).

Using the aforementioned energy equation, we get:

Annual Energy Savings = 296 (AHU cooling load in KW x 0.26 + Fan Motor KW) x hr-saved/year

Annual Energy Savings for 35 AHU-PAU *= 296 (5,763 x 0.26 + 198.67) KW x hr-saved per day*
= 498,557 KW x hr-saved per day

Annual Cost Savings for 35 AHU-PAU *= HK$0.8 x 498,557 x hr-saved per day*
= HK$ 398,846 x hr-saved per day *(10)*

By referring to the method as presented in *Table 4-1* of Chapter 4, annual cost savings (35 AHU-PAU) for different HVAC operational schedules using the *Active Control Approach* for Radon Management can be estimated. The results are shown in *Table 5-1.*

Operational Schedules of AHU-PAU	***Radon in Bq/m^3 at 9 am $C_{(9:00)}$***	***Vent-on-hrs***	***Hrs saved from "Now" per day***	***Estimated Annual savings for 35 AHU-PAU in KW***	***Estimated Annual savings for 35 AHU-PAU in HK$***
"Now"	260.6	12	N/A	N/A	N/A
1	198.3	16	-4	N/A	N/A
2	202.4	12.5	-0.5	N/A	N/A
3	203.9	11.6	0.4	199,422	160,000
4	204.9	10.7	1.3	648,123	518,000
5	195.6	9.9	2.1	1,046,969	838,000

Table 5-1. Financial Assessment on *Active Radon Control Approach* using Cost-effective AHU-PAU Scheduling Strategy

Where,

1. "Now" stands for the present HVAC system operation
2. N/A stands for Not Applicable
3. C stands for radon concentration in Bq/m^3 at any specified time
4. 1 KWh (kilowatt per hour) of electricity costs HK$0.8
5. Number of working/studying days in a year is 296

2. Annual Savings of *Active Radon Control Approach* by 166 AHU-OAD

As described in the *EngD Portfolio Submission 4*, the total number of AHU is 201, of which 35 sets are serving PAU for pure outside fresh air intake of some 2,594 FCU in the university campus. Most of these FCU are installed in classrooms and offices, whereas, the remaining 166 sets of AHU receive outdoor air through the fresh air ducts as controlled by the OAD.

Using the computerised FASER Energy Accounting System[39] , an estimation of energy savings can be obtained by application of the OAD scheduling for the 166 AHU of HKUST. This is based on the assumption that instead of terminating the full set of AHU, the outdoor air damper will be programmed according to the ON-OFF schedules required.

To simplify the energy savings estimation, the FASER computer software, as operated by Honeywell Limited, Hong Kong makes the following assumptions during computation of AHU energy savings:

a. Power Factor (P.F.) = 0.9
b. % load = 0.85 (Percentage load with 0.87 % Motor Efficiency)
c. KW/Tr = 0.75 (Kilowatt per Refrigeration Ton)

c. delta_h = 5 (Enthalpy difference between outdoor air & building internal conditions, averaged over latest years in unit Btu/lb dry air)

d. cfm (/KW) = 1,250 (Cubic Feet per Minute)

As derived from Chapter 2,

KW/Tr= 1.11 (Kilowatt per Refrigeration Ton)

One of the essential energy equations in the FASER software[39] is:

AHU Savings in Energy = 4.5 x delta_h / 12,000 x KW/tr x %load x cfm per KW x hr-saved
= 4.5 x 5/12,000 x 1.1 x 0.85 x 1,250 x per motor-KW x hr-saved
= 2.19 x per motor-KW x hr-saved

That is, the annual energy savings for each AHU using the operational strategy of Cost-effective outdoor air damper (AHU-OAD) can be estimated by:

Annual Energy Savings for 166 AHU-OAD = 2.19 x AHU cooling load in KW x Hours saved/ year
= 296 x 2.19 x AHU cooling load in KW x hr-saved/ day
= 648.24 x (1871.02-198.67) x hr-saved per day
= 1,084,084 x hr-saved per day

So,

Annual Cost Savings for 166 AHU-OAD = HK$ (0.8 x 1,084,000) x hr-saved per day
= HK$ 867,267 x hr-saved per day (11)

By referring to the method presented in *Table 4-1* of Chapter 4, Annual Cost Savings (166 AHU-OAD) for different HVAC operational schedules using the *Active Control Approach* of Radon Management can be estimated.

The details are shown in *Table 5-2*.

Operational Schedules of AHU	*Radon in Bq/m^3 at 9 am $C_{(9:00)}$*	*Vent-on-hrs*	*Daily Hrs saved from "Now"*	*Estimated Annual Savings for 166 AHU-OAD in kilowatt (KW)*	*Estimated Annual savings for 166 AHU-OAD in HK$*
"Now"	260.6	12	N/A	N/A	N/A
1	198.3	16	-4	N/A	N/A
2	202.4	12.5	-0.5	N/A	N/A
3	203.9	11.6	0.4	433,634	347,000
4	204.9	10.7	1.3	1,409,309	1,127,000
5	195.6	9.9	2.1	2,276,577	1,821,000

Table 5-2. Financial Assessment on *Active Radon Control Approach* using Cost-effective AHU-OAD Scheduling Strategy

Using the same method presented previously, we get:

1. N/A stands for Not Applicable
2. C stands for radon concentration in Bq/m^3 at any time specified
3. 1 KWh (kilowatt per hour) of electricity costs HK$0.8
4. Number of working/study days in a year is 296

3. Total Annual Savings for the *Active Radon Control Approach*

Total annual savings for the *Active Radon Control Approach* for the aforementioned energy-efficient HVAC operational schedules are estimated as:

- For Operational Schedule 3: HK$(159,000 + 347,000) = HK$0.5 M (say)
- For Operational Schedule 4: HK$(518,000 + 1,127,000) = HK$1.6 M (say)
- For Operational Schedule 5: HK$(837,000 + 1,821,000) = HK$2.7 M (say)

(where, M = Million of HK Dollars)

5.3 MANAGEMENT STRATEGY USING AN *PASSIVE RADON CONTROL APPROACH*

The *Passive Radon Control Approach* using the management strategy of covering the radon entry route in a HVAC environment is found to be a successful energy-efficient method to maintain acceptable indoor radon concentrations. The methods and results have been presented in Chapter 4.

The energy consumption for individual AHU after the internal surfaces including walls and floors are treated with Polyurethane-based paints has also been identified in Chapter 4. It indicated that when all internal room surfaces of room floor and walls are coated with P-u paints, the variables become:

R is 4.8 Bq/m^2/hr (radon emission rate from the internal room surface),

C_o is 31.22 Bq/m^3 (concentration just before the HVAC system was turned off), and the rest of the variables are the same.

Table 4-2 in Chapter 4 gives evidence of indoor radon concentrations being reduced after application of Polyurethane-based paints on internal room surfaces. The mathematical *models (10)* and *(11)* used in *Active Radon control Approach* are also used:

1. Annual Savings for *Passive Radon Control Approach (PRCA)* by 35 AHU-PAU

Annual Cost Savings for 35 AHU-PAU = HK$ 398,846 x hr-saved per day *(10)*

Thus,

Cost Savings after application of PRCA for 35 AHU-PAU = HK$ 398,846 x 4 or HK$1,595,000

2. Annual Savings for *Passive Radon Control Approach* by 166 AHU-OAD

Annual Cost Savings for 166 AHU-OAD = HK$ 867,267 x hr-saved per day *(11)*

Cost Savings after application of PRCA for 166 AHU-OAD = HK$ 867,267 x 4 or HK$3,469,000

3. Total Annual Savings for *Passive Radon Control Approach*

Total Annual Savings for *Passive Radon Control Approach* using the aforementioned Polyurethane-based internal surface coating are estimated as:

HK$1,595,000 + HK$3,469,000 = HK$5 M (say) where M = Million

Table 5-3 provides the result of the *Approaches* in an easy reference format.

Polyurethane –based Painting	***Radon in Bq/m^3 at 9 am $C_{(9:00)}$***	***Vent-on-hrs***	***Hrs saved from "Before" per day***	***Estimated Annual savings after applied P-u paints in KW***	***Estimated Annual savings after applied P-u paint in HK$M***
"Before"	260.6	12	N/A	N/A	N/A
After	189.1	6	6	N/A	5M

Table 5-3. Financial Assessment of *Passive Radon Control Approach* using P-u paint Surface Coverings

4. Payback period for P-u Painting Project at HKUST

The HVAC area of the Hong Kong University of Science & Technology measures approximately 0.15 Million square metres (sq. m.). As an estimate for a complete coating of all internal surfaces of offices, classrooms and laboratories etc., it is reasonable to use a multiplier of 4 on the constructed floor areas. Actually, some of the partition walls and ceilings are made of gypsum boards which are not required to be surface treated due to the low radon emission as found in chapter 4. Thus, (4 x 150,000) or 600,000 sq. m. of internal room surface area is estimated as the area needing P-u paint coating.

Of the material cost of P-u paint and its associated labour cost, HK$70 is estimated for coating each sq. m. area of internal room surface. Roughly speaking, 0.6 Million sq. m. requires HK$(70 x 600,000) or HK$ 42 Million. On top of this, other expenses amounting to HK$100 per each sq. m. of HVAC floor area are also required to pay for the overheads, miscellaneous, labour and materials etc. relating to carpets, floorings, and ceilings, moving of furniture and equipment prior to and after the coating exercises. This work alone will be another (150,000 square metres x HK$100) or HK$15 Million making the total cost of HK$57 Million.

With an estimated annual energy savings of just over HK$5 Million, as projected in the previous sections, this P-u painting project will have a payback period of approximately 10 years' time by applying the Simple Payback Period Method and 12.6 years' time by the Discounted Payback Period Method. Details are shown in *Appendix C*. For a large project of this size with extended project time, a discounted payback approach to account for the present value figures is normally used.

5.4 DISCUSSION

a. From the engineering point of view, energy conservation is a global concern especially when it links up with the environmental and health issues of radon. A direct estimation of the benefit from the cost savings might not be exhaustive since this exercise is not only beneficial to the university's financial administration, but can also have a benefiticial impact on the earth and the environment. This illustrates the high demand for this type of research possibly leading to a better world and also a healthier environment for the residential staff and students.

b. This study has provided an effective solution to those who worry about the problem of radon exposure, especially those users who spend most of their time inside a "tight" HVAC building environment (i.e. with locked windows).

c. The radon associated health risk needs to be communicated in a more effective way, such as public service announcements, general education, information fact sheets, etc.

d. The findings of this project contributing to this concrete forest of living are significant, leaving us a healthier indoor air HVAC environment with acceptable radon risk level while at the same time saving energy.

5.5 CONCLUSIONS

The results of this engineering management study yield the following conclusions:

1. Potential energy savings for the implementation of the energy-efficient *Active Radon Control Approach* by applying "Cost-effective HVAC Operational Scheduling" can yield a saving of approximately 2.7 Million Hong Kong Dollars a year; and

2. Potential energy savings for implementation of the energy-efficient *Passive Radon Control Approach* by applying Polyurethane-based paint covering on internal surfaces of building structures can yield approximately 5 Million Hong Kong Dollars annually with a discounted payback period of about 13 years.

Chapter 6

DISCUSSION

6.1 Legal Requirements in Hong Kong

In Hong Kong, there is currently no strict legal requirement to control the indoor radon exposure for the people of Hong Kong in either residential or occupational settings. However, overseas guidelines, in particular the established ones in the United Kingdom, have been adopted or recommended. The question as to whether or not the existing radon concentrations at HKUST are at the level of concern or one which requires government action, etc. is still a debatable topic. The Environmental Protection Department of Hong Kong has been working diligently during recent years to conduct a radon survey, to hold a public inquiry, and to formulate legislative requirements if and as appropriate.

6.2 Radon Health Risk from a Financial Impact Viewpoint

The UNSCEAR projected a high lifetime risk of lung cancer as a result of radon exposure [3]. The lifetime risks (LTR) of death rates for non-smokers and smokers at an exposure of 200 Bq/m^3 WHO level were estimated at 10 per 1000 and 100 per 1000 population respectively. In comparison, LTR from fire death has been estimated at 1 per 1000 and traffic accident death at 10 per 1000[40]. Furthermore, epidemiological studies, animal experiments and radiobiological effects were employed[41] to better quantify radon health risk. Lung cancer rates were found to elevate with increased radon exposure on most of the miner studies[42]. The International Agency for Research on Cancer concluded that there was sufficient evidence to classify radon as a carcinogen for human beings[43]. Radon-exposed animal[42] studies also demonstrated a possible cause-effect relationship. Epidemiological findings have been used to project possible lung cancer risk of populations exposed to radon daughters[1].

After sampling 90 HVAC areas at HKUST, the daily average radon level was measured at 107 Bq/m^3 which is within the WHO limit of 200 Bq/m^3. With this result, is remedial action required? At this level, what is the magnitude for the health risk? Will it subject HKUST to a significant financial burden in exchange of an insignificant magnitude of health benefit? Applying the basic principle of radiation protection, "As Low As Reasonably Achievable (ALARA)", is the WHO exposure level limit of 200 Bq/m^3 appropriate for the HKUST community? Is it necessary to be seriously concerned about the intermittently high radon level exposures identified at HKUST? A good balance of heath risk and cost benefit is sometimes difficult to determine, but critical for HVAC building operators in managing the indoor HVAC environment.

An international radiation protection article[6.2] reported that "Radon accounts for 50% of the radiation dose the UK public will, on average, receive in a lifetime: Because it is natural, the risks should be ignored?". It brought the concern to the attention of the public. In this report, 250,000 radon samples collected from residences gave a finding of 23,000 locations with high radon levels in excess of the WHO limits[40]. The author stated "It is very interesting to speculate if occupants of these high radon areas would be willing to pay UK£300 to £800 in order to reduce the risk of lung cancer from radon exposure to levels similar to a lethal fire at home or a fatal accident on the road". Actually, this question could be asked of any other regions in the world with elevated levels of radon, since the financial issue is always one of the major elements to be considered. The cost-effective *Radon Control Approaches* employed in this study will provide a workable solution. The implementation of radon management approaches discussed does not require significant financial resource in order to bring high intermittent exposure down to the WHO standard. With little financial implication, the building operators can focus on addressing the radon health risk in a energy-efficient HVAC environment. With this tool, management decisions are made easy.

The study at HKUST can also be beneficial for risk communication. Through a series of sampling activities, promotions and seminars, the occupants can be made fully aware of the radon health risk in their living and work environments.

6.3 An Inexpensive and User-friendly way to identify Peak Radon Levels

A number of methods for assessing radon levels have been presented in detail in Chapter 2 and in the *EngD Portfolio Submission 2.* They can be summarised in three broad categories, namely, grab or spot sampling, continuous sampling and integrated sampling. Scientists can easily make a choice of sampling strategy and equipment simply by evaluating which type of information is desired, the availability and sensitivity of the instrumentation specified, etc.

As shown in Chapter 2, an average radon consideration in a HVAC environment is easy to obtain by just using some handy passive sampling devices like charcoal canisters. They can be employed by leaving them for a few days in the areas to be sampled, and subsequently delivering them to a laboratory for analysis. However, the situation will not be as simple in cases where building operators are required to define the peak radon levels in a particular area serviced by the HVAC system. Chapter 2, on radon assessment, yields an outcome with good correlation found between the real-time, active radon sampling results and passive sampling results. This approach has been further extended to a valuable finding that an inexpensive charcoal canister system can be used to predict the peak radon levels in a HVAC environment by using *models* similar to the following:

$C_{Rad7} = 11.24 + 1.25\ C_{canister}$ (*model (1)* of Chapter 2)

$(r = 0.97,\ r^2 = 0.94,\ p<0.01)$

$C_{peak} = 17.22 + 2.31\ C_{daily}$ (*model (2)* of Chapter 2)

$(r = 0.96,\ r^2 = 0.91,\ p<0.01)$

Due to the variation of the two radon measuring techniques, the results obtained from the RAD7 Continuous Monitors and Charcoal Canisters' radon counting system were found to deviate slightly from one another. Using *model (1)*, the building operators can interpolate the results of the daily average levels obtained by charcoal canisters, $C_{canister}$ to project the daily average radon levels of the RAD7 Continuous Monitor, C_{Rad7}. Then, by inserting the C_{Rad7} result into *model (2)* as a value of C_{daily}, the peak radon concentrations, C_{peak} of the day can be predicted.

6.4 Influences on Radon Levels in a HVAC Environment

As discussed in Chapter 2 and the *EngD Portfolio Submission 2*, there are a number of factors which can influence the ultimate indoor concentrations of radon and radon progeny to which residential or workplace occupants are exposed. These can be categorised into three major elements, namely, the "source strength" of radon-bearing materials (soil, water and building materials etc.), the "structural characteristics" of the premises (which affect radon entry and removal) and the meteorological conditions[28]. In Chapter 2 of this Executive Summary, the results of the HKUST radon study have been shown to be influenced significantly by the air exchange facilities, which were classified as a "structural characteristic".

Generally speaking, the basic mechanisms leading to air exchanging between indoor and outdoor environments can be summarised under "Infiltration", "Natural Ventilation" and "Mechanical Ventilation" [28]. The radon management experiments conducted in this project indicated that radon levels were affected heavily by "Mechanical Ventilation" but not the other two. The modern technology designed and installed in the environmental control system at HKUST made this third mechanism the most important factor. To conclude, the "Mechanical Ventilation" facilities, such as the air handling units and fume cupboards for the case of HKUST, significantly influence the indoor radon concentrations.

In fact, the HKUST campus has more than 200 fume cupboards in the laboratory complex. The presence of fume cupboards significantly affects indoor radon levels ($t = 4.08$, $p < 0.01$). The HVAC environment of these laboratory areas is maintained automatically by a sophisticated computerised Building Management System, the BMS. The safety features of the laboratory facilities include the setting of a slightly negative pressure in the majority of these indoor laboratory environments. This ensures the environmental control system is capable of providing good containment of all smell, particles and gases generated from the research environment in case the local fume exhaust system is ineffective. The maintenance of negative pressure in the indoor environment of the laboratory areas requires an increase of air exchange rates. In addition, the direct local fume extracting system (other hoods, canopies, etc.) produces the same effect.

Another major influence on indoor radon concentrations at HKUST is "Soil Contact", a factor of source strength as presented in the *EngD Portfolio Submission 2*. Radon diffuses from soil through cracks in foundations, drains and other pathways, making its way into the indoor environment of the premises or buildings. The results in Chapter 2 confirm this basic principle that indoor radon concentrations measured in HKUST areas, which are in contact with the ground soil, are found to be significantly higher than those above the ground levels ($t = 2.68$, $p<0.01$).

6.5 Relationship between indoor and outdoor radon concentrations

There are three possible relationships: indoor levels higher than outdoors; indoor levels lower than outdoors; or, they are about the same. Based on this observation, it is not surprising when some studies indicate there is a weak correlation between the measured radon concentrations and air exchange rates[44]. In other words, this influence on "structural characteristics" due to changing the air exchange rate was found to have no significant impacts on the indoor radon concentrations. This can be explained by the fact that these data were collected in low-rise residential premises with outdoor radon levels close to those indoor concentrations so that changing the exchange rate by opening windows to improve the fresh air intake has no observable effect on the indoor concentrations.

Under other circumstances, as brought out in the *EngD Portfolio Submission 1*, the increase of air exchange rate in some countries was even found to have negative effects on indoor radon reduction[45]. The study showed that introduction of outdoor air to the indoor environment was found to increase the indoor radon concentration because the outdoor air occasionally had a radon level higher than those indoors. A similar situation is that of a congested city with limited land, where some air intake points for the HVAC system of the buildings have been located at underground basement levels or just above ground level where radon levels are generally elevated. This design contributes to a high radon content of intake air to the indoor environment due to the release of radon from the ground soil and surrounding basement walls. In such cases, the "fresh air" drawn into the buildings may carry an elevated amount of radon, which in fact has been found in a few places in HKUST.

For most of the urbanised areas, buildings are constructed with concrete containing high uranium-bearing materials. Because of this high concentration of radon emitting material in the building environment, indoor radon concentrations are much higher than those of outdoors, particularly in those environments with "locked windows" and re-circulated HVAC system. This is exactly the case found in most areas of Hong Kong including HKUST. Another factor to consider is the seasonal variation of outdoor radon levels. The "meteorological condition" in some countries may cause significant fluctuations of outdoor radon levels following the change of seasons of the year[44].

On the whole, the relationship between the outdoor and indoor concentrations is an important factor when a decision is to be made on whether the *Active or Passive Control Approach* is to be implemented.

6.6 Applications of *Radon Level Predictive Models*

As presented in Chapters 4 and 5, the radon concentrations, $C_{(t)}$ under different conditions of HVAC operations can be accurately estimated by applying the derived *radon level predictive models* shown below:

a. *With the HVAC system OFF:*

$$C_{(t)} = C_o + RLt$$ (*model (4)* of Chapter 3)

b. *With the HVAC system ON*:

$$C_{(t)} = \frac{RL}{MN - k}\,[\exp(-kt)-\exp(-MNt)]+(C_{o'}-C_{in})\exp(-MNt) + C_{in}$$

(*model (8)* of Chapter 3)

Where, Modifier $M = 0.65 - 0.1N$ (*model (9)* of Chapter 3)

Using the above *models* (see *Fig 4-1* of Chapter 4) as a predictive tool, the operating schedules of the air handling units (AHU) in the HVAC system can be adjusted easily with different On/Off times. Optimal effects can then be achieved with the best combinations of radon levels and energy usage, such as, the early activation of the HVAC system at the beginning of the work day together with the early shut down of the system towards the end of the regular work day. In HKUST, the On/Off commands of the individual HVAC air handling units can also be carried out via the computerised Building Management System (BMS), with no demand for extra manpower as an operational constraint. The BMS time-event programme, after inputs of the On/Off timing details, can operate the individual air handling units automatically and round-the-clock in accordance to the pre-set schedules. Any shifting of these operating schedules can be easily accomplished.

By applying the *Active Radon Control Approach*, indoor radon concentrations of a HVAC environment can be maintained below the desired level (e.g. kept below the WHO standard of 200 Bq/m^3) and the operational hours of AHU can also be reduced to save energy. This operational strategy has been described in detail in Chapters 4 and 5.

In addition to this, the *Active Radon Control Approach* developed in this project is suitable for application in areas where the radon action levels are different from the WHO limit of 200 Bq/m^3. As discussed in Chapter 2 (also show in *Table B-2* of *Appendix B)*, some countries, like Canada, Netherlands and United States have established different radon reference exposure standards, which are 800, 20 and 150 Bq/m^3 respectively. By referring to the radon concentration patterns presented in *Fig 4-1* of Chapter 4, the horizontal WHO 200 Bq/m^3 line in the figure can be shifted upwards or downwards to meet the required 800, 20 or 150 Bq/m^3 action levels of these countries. Using different sets of input parameters for the *models (4), (8)* *and (9)*, other sets of simulated data can be obtained to predict the radon patterns to suit the specified standards along with the radiation protection principle of ALARA (As Low As Reasonably Achievable).

6.7 Preferential Application of the *Passive Approach* to New Constructions

Since the application of Polyurethane-based paint has been found in this study to be an effective passive control measure for reducing radon emission, it can be employed to reduce exposure. However, it would be difficult to apply this *Approach* in an already-occupied building due to the logistical challenges of moving people, furniture and equipment to enable comprehensive painting of all room surfaces. On the other hand, the *Passive Radon Control Approach* should be seriously considered for new and unoccupied buildings since painting, in such cases, would be quite easy to accomplish. Moreover, one must keep in mind the potential hazard associated with this *Passive Control Approach* as P-u paints include the use of various organic solvents which will become a source of indoor pollutants, i.e. volatile organic compounds. Furthermore, from an aesthetic viewpoint, using a P-u paint base primer may limit the choice of the final finishing coat of paints since the latter may be incompatible to apply on top of the P-u paint with shiny surfaces.

When applying P-u paint coating on building walls, the key factor for the paint to provide an effective barrier for radon emission appears to be its ability to form a complete seal over concrete wall surfaces. The ability of the P-u paint to provide a completely sealed coating, in turns, depends on a number of parameters. These include the cleanliness of the wall surface, the type of primary base coating, the trapping capability of coating for air and water, the coating thickness, the adhesive properties of paint, etc. The long term effectiveness of the P-u paint in reducing the radon concentration also needs to be investigated.

A measurement protocol for residential and non-residential buildings for new constructions in Hong Kong was being studied by the Hong Kong Environmental Protection Department and had been circulated amongst the private and public sectors in Hong Kong for review and comment in 1996. The protocol calls for random radon measurements in pre-defined study units with a fixed air exchange rate. These radon control guidelines are published in the form of a "Practice Note for Professional Persons" providing appropriate guidance for reduction of radon exposures. This protocol, if adopted, may provide another strong reason for applying the *Passive Control Approach* to new constructions. The average radon concentration is recommended to be lower than the territory-wide mean concentration of 100 Bq/m^3 and in any case, any individual measurement should not exceed the 200 Bq/m^3 limit.

6.8 Estimating Project Payback of the *Passive Approach* using SPPM and DPPM

During the cost estimation stage for the P-u Painting Project, as given in Chapter 5, a lot of difficulties and uncertainties have been encountered due to the enormous project size, and the risk and potential cost associated with relocating sophisticated and expensive equipment in laboratories. In addition, accurate energy savings and payback period are difficult to project. A lot of assumptions are also needed. These include the labour costs, the repair and maintenance costs, the depreciation items, the taxation rate, the interest and inflation rates etc. Generally speaking, when evaluating an energy-related improvement project, where equipment life can be easily determined and where the relationship between future costs remains constant, a Simple Payback Period Method (SPPM) can be applied. The justification for payback period is important especially when this payback is over 5 years and a lot of unexpected influences may arise during the period. The SPPM might not be appropriate when all these factors are put together for detailed consideration.

The SPPM has been challenged due its accuracy in energy studies especially when the economic criteria need to be determined at an early stage. The SPPM does not take into account the time value of money; it is an easy and inexpensive way of making a fast estimation of a project as indicated in Chapter 5. Moreover, despite conceptual drawbacks of the payback simple technique, this project-screening device can still exist over the years. Lots of financial evaluations still involve SPPM because it tells them something they want to know quickly. Commercial Sectors that are short of cash will necessarily place a higher value on projects with a higher degree of liquidity. A project that returns its investment quickly will allow these funds to be re-invested quickly in other projects. It can also be used as the indicator of the project's relative risk since firms can usually forecast near-term events better than distant ones.

The Discounted Payback Period Method (DPPM) takes into account the time value of money by finding the present value of the expected net cash inflows of the investment project. It is then discounted at an appropriate percentage rate and subtracted from the initial cost outlay. This approach attempts to translate costs and revenues to be received at a time in the future to the equivalent amount that would be received at the present time, after discounting the effects of interest. For the estimation of this *Passive Radon Control Approach* project for P-u painting in HKUST, DPPM is considered more accurate and preferable. As shown in Chapter 5, the payback period using DPPM became approximately 13 years after inclusion of the present value factor into the financial evaluation. The result, using this DPPM, is about 3 years longer in payback time than the result using the Simple Payback Period Method (10 years).

6.9 Combining *Passive* and *Active Approaches* in controlling radon levels

Before implementation of any radon control measures, it is critical to perform a thorough financial analysis, similar to any construction or renovation project, of the installations and operational costs involved. One of the major objectives of this study is to address this issue. Intensive involvement of the occupants during the planning and implementation stages, is also a key to success.

Generally speaking, the employment of BOTH the *Active and Passive Approaches* in addressing the radon issue may be considered and the combined effect evaluated. However, in an already operating facility, opportunity for such application appears limited. This is due to the logistical difficulties in relocating people and equipment to effect a thorough painting of the facility. While the application of P-u paint has proven to be effective in reducing radon emission, its application is better implemented in new facilities before occupancy and prior to installation of utilities. At the present moment, all HKUST facilities are fully operating and any rooms are loaded with instrument and utility penetration. It would be a monumental task to perform a thorough post operational painting of all surfaces in these occupied areas. Also, a lot of complication and hidden costs of the project will be involved. In the future, when new facilities are built, it will be most interesting to perform an evaluation of the combined effect of both options.

From a financial point of view, the long payback period of the *Passive Radon Control Approach* appears to be an unfavourable investment. However, the *Passive Radon Control Approach* can be applied in some areas, better than the *Active Radon Control Approach*, such as those with ground soil contact. This is due to the importance of "Source Strength" which can significantly influence the indoor radon concentrations in such indoor HVAC environments as confirmed in Chapter 4. The energy-efficient management strategy to reduce indoor radon by sealing of the radon entry routes as evaluated in this study confirmed a high degree of feasibility.

Also, the results of the climate chamber experiment in Chapter 4 demonstrated that the effectiveness of radon reduction using the *Passive Approach* can be further improved with an additional layer of the P-u paint coverings on the internal surfaces of building. In other words, for the indoor environments measured with extraordinary high radon concentrations, the *Passive Radon Control Approach* using P-u painting appears to be an effective way to address the radon problem.

The developed *Active Radon Control Approach* produces high flexibility and simplicity for the users to adapt into different environments having different requirements of radon action levels. For the case of an indoor environment with high complexity in usage and pro-longed HVAC operational hours for the laboratory areas in particular, the *Passive Radon Control Approach* will undoubtedly cause disturbance or interference of the operation of the university. The *Active Radon Control Approach*, through a series of improved HVAC operational schedules for energy optimisation, is more appropriate to be introduced to all laboratories, classrooms, offices and corridors above ground level.

6.10 Dose Reduction and economic implications for *Active and Passive Approaches*

When dose reduction is to be considered, attention is drawn to the Publication of International Commission of Radiological Protection[46] (ICRP60) which emphasises the need for radiological protection both in dwellings and workplaces. ICRP60 distinguishes two circumstances of exposure to radiation. One where human activities introduce new sources or modes of exposure and thus increase the overall exposure and the other where they decrease the exposure to existing sources[46]. The first circumstance is considered as "practices" and the second "intervention". This EngD study belongs to the "intervention" category with the goal of optimising radiological protection with a balance of health and cost benefit. Care should be taken to evaluate whether the reduction in dose is sufficient to justify the level of harm and the costs involved, including social costs, of the "intervention"[4].

As discussed previously, there are no specific regulations on radon exposures in Hong Kong. Following the ICRP60, the ICRP65[4] "Protection against radon-222 at Home and at Work" in 1993 deals exclusively with radon in homes and dwellings and provides guidance on radon concentrations above which remedial measures are required to be taken. It also discusses the scientific evidence on the health effects of radon exposure and recommends the adoption of an action level within the range 200-600 Bq/m^3 for dwellings[4]. ICRP 65 also emphasises that workers who are not regarded as being occupationally exposed to radiation are usually treated in the same way as the general public. By considering this, it is logical to adopt an action level for "intervention" in the workplace of HKUST at the same level of effective dose as action levels for dwellings, using the ALARA (As Low As Reasonably Achievable) principle to maintain the indoor radon concentration at about 200 Bq/m^3.

For man-made radiation, action based on the ALARA principle can result in a substantial reduction in doses to levels well below the dose limit[47]. ICRP60 states that "a linear relationship between incremental dose and the incremental probability of a deleterious effect will be an adequate approximation". It implies that, for our case of natural radiation resulting from radon exposure, the radiation risks are also proportional to the dose. This can help when we try to evaluate risks from the measurements of dose[47]. In a natural environment, people exposed to radon will also adsorb doses from other natural sources of radiation at the same time. The intention of converting Radon Exposure Reduction using *Radon Control Approaches* developed in this EngD study to effective dose reduction is sensible from a radiation protection viewpoint.

It is convenient to consider the potential alpha energy concentration (PAEC) of a mixture of short-lived radon decay products (RDP) in air[27]. This is the sum of the alpha energies that RDP will emit during decay. At radioactive equilibrium, if no RDP are lost, there will be equal activities of radon and all its RDP in air. Under these circumstances, 1 Bq/m^3 of radon is equivalent to a PAEC of $5.56x10^{-9}$ Jm^{-3}. However, due to complicated indoor conditions such as those concerned with ventilation, aerosol concentration and characteristic, radioactive equilibrium can rarely be reached[27] in practice. The equilibrium equivalent radon concentration is the concentration of radon gas, in equilibrium with its RDP, which has the same PAEC mixture in question. Whereas, an equilibrium factor is the ratio of the PAEC for the actual mixture of RDP to that which would apply at radioactive equilibrium. The historical unit of PAEC, the Working Level (WL) is defined as 2.1 10^{-5} Jm^{-3} and a Working Level Month (WLM) is defined as exposure to 1 WL for a working month of 170 hours.

To realise the annual lung dose due to radon and RPD, this study adopted the ICRP approach which introduced a time-integrated exposure to radon with a relationship of $1.6x10^{-6}$ WLM per $Bqhm^{-3}$ at an equilibrium factor of 0.4 under 2000 hours of work a year[7]. This further produces a recommendation of an appropriate annual dose of 4 mSv WLM^{-1}, which has been confirmed by a recent study[48] with a close figure of 4.2 mSv WLM^{-1}. This is acceptable for the general public in dwellings with high aerosol concentration in sizes $>4x10^4$ particles per cm^3[48]. In fact, another study[47] also confirms that a good estimate of the equilibrium factor of 0.43 was obtained after a survey of 94 air-conditioned offices in Hong Kong.

a. <u>Annual Dose Reduction Resulting from the *Active Radon Control Approach*</u>

With reference to results given in *Table 5-2* and *5-3* of Chapter 5, Annual Cost Savings for different HVAC operational schedules after implementation of *Active Radon Control Approach* are reprinted in *Table 6-1*. With the mathematical approach stated above, the corresponding dose reduction per year at work for different HVAC Operational Schedules are given in *Table 6-1*.

Operational Schedules of AHU	*Radon Levels in Bq/m^3 at 9 am, $C_{(9:00)}$*	*Estimated Annual Savings (in HK$M)*	*Simulated Mean Radon Exposure* in $Bqhm^{-3}$ (per day of work)*	*Annual Exposure Reduction (from "Now" in $Bqhm^{-3}$)*	*Estimated Annual Dose Reduction (from "Now" in mSv)*
Now	260.6	N/A	741.8	N/A	N/A
1	198.3	N/A	626.9	28,725	0.184
2	202.4	N/A	633.6	27,050	0.173
3	203.9	0.5M	636.3	26,375	0.169
4	204.9	1.6M	637.8	26,000	0.166
5	195.6	2.7M	620.4	30,350	0.194

Table 6-1. Estimated Annual Dose Reduction after application of the *Active Radon Control Approach* using Cost-effective AHU-OAD Scheduling Strategy

*Where, *Simulated from SigmaPlot Software[36] with "Now" represents the existing Operational Schedule of HVAC system*
(Fig 4-1 in Chapter 4 shows the radon profiles), and

HK$M = Million Hong Kong Dollars

b. Annual Dose Reduction Resulted from *Passive Radon Control Approach*

With reference to results given in *Table 5-4* of Chapter 5, the Annual Cost Savings after implementation of the *Passive Radon Control Approach* can be estimated as summarised in *Table 6-2*. The corresponding dose reduction per year at work due to the use of Polyurethane-based Painting is given in *Table 6-2*.

P-u painting applied	*Radon Levels in Bq/m^3 at 9 am, $C_{(9:00)}$*	*Estimated Annual Savings (in HK$M)*	*Simulated Mean Radon Exposure* per day of work (in Bqhm^{-3})*	*Annual Exposure Reduction (from "Before" in Bqhm^{-3})*	*Estimated Annual Dose Reduction (from "Before" in mSv)*
Before	260.6	N/A	741.8	N/A	N/A
After	189.1	5M	546.6	48,800	0.312

Table 6-2. Estimated Annual Dose Reduction after application of *Passive Radon Control Approach* using P-u Paint Surface Coverings

*Where, *Simulated from SigmaPlot Software[48] with "Before" represents the existing situation of no P-u painting on internal walls*
(Fig 4-6 in Chapter 4 shows the radon profiles), and
HK$M = Million Hong Kong Dollars

The above dose values above compare with the recently-derived total dose from natural radiation in Hong Kong of 2.7 mSv y^{-1}[49] (2.4 mSv for UNSCEAR 88 and UNSCEAR 93)[6],[50]. This confirms again that the two *Radon Control Approaches* introduced in this EngD study are cost-effective with added health benefits. The resulting percentages of dose reduction of 7.2 % and 11.6 % (0.194/2.7 and 0.312/2.7), respectively for the *Active* and *Passive Control Approaches*, are encouraging as they are also proportional to the cancer risk reduction when the dose convention of ICRP is adopted[47].

NRPB estimated that an annual dose of 1 mSv is capable of contributing a lifetime risk of about 1 in 300 lung cancer deaths if exposed to Radon and its decay products[51]. In our *models*, the *Active* and *Passive Control Approaches* will lead to an annual dose reduction of 0.194 mSv (say, 0.2 mSv or 120 Bqhm^{-3} radon exposure per workday) and 0.312 mSv (say 0.3 mSv or 200 Bqhm^{-3} radon exposure per workday) respectively. In other words, with a total campus population of approximately 10,000 at HKUST, these dose reductions mean reducing cancer deaths in our campus community by between 7 and 10 lives.

From a monetary point of view, some environmental scientists[52] use a figure of US$2 Million per life saved to calculate the financial benefit. With the annual radon dose reduction of 0.2 and 0.3 mSv, an additional annual society gain of 1.5 and 2 Million Hong Kong dollars can be achieved through human life savings, respectively, by the application of *Active* and *Passive Approaches* (an average human life span of 70 years has been assumed). That is to say, the gross financial benefits for the two *Approaches* explored from this study are between 4.2 and 7 (i.e. 2.7 + 1.5 and 5 + 2) Million Hong Kong Dollars.

However, the social cost estimation of a human being might not always be a subject of agreement. The deviation can be very large[53] and the figures provided are derived for American society, which may not be directly applicable in Hong Kong. Application of different figures may yield very different results, which can cause decision making to be very difficult if different life costs are used. This assessment can only be used as a guide in this case, and should not be compared directly to the achievements generated by utility savings. This suggestion will be further elaborated in the next section.

To summarise, this research demonstrates significant gains both in terms of saving in utility cost and, though difficult to quantify in dollar figures, additional gain in cancer death reduction. In a way, the *Radon Control Approaches* developed from this EngD study do not result in any noticeable expenditure but, on the contrary, generate two types of significant benefits (both economical and social).

6.11 Additional Considerations on ALARA and HVAC Operational Constraints

Nowadays, people are becoming more conscious of health issues and in particular, of those related to life-threatening substances in the general environment. This includes, for instance, the relationship between human health and exposure to the peak or average levels of these environmental and radioactive substances such as radon. Frequently asked questions include what level of exposure will result in damage to human health and what is the health implication when the exposure level is excessively high but for a comparatively short duration. The *Radon Control Approaches* developed from this study have been heavily based on the WHO recommended guideline (200 Bq/m^3) in comparison with the obtained peak concentrations in the campus-wide survey. The criteria may appear conservative but can be justified because of the long working and studying time of the university occupants.

By referring back to Chapter 3 of this Executive Summary, a continuous monitoring device, RAD7 was being used as an essential instrument in the experiments. The characteristics of how radon builds up until the arrival of peak concentrations were obtained in addition to the average radon concentration or exposure level, which is typically obtained by the charcoal canisters and alpha track drop-in measuring devices. The canisters and alpha-track devices are limited to obtaining the average radon exposure measurements. The university occupants benefit from the modern radon detection instrumentation used in developing the *Radon Control Strategies* because the concern on short-term exposure with levels exceeding the WHO guideline can also be explored. On the other hand, this application of the *radon level predictive models*, with emphasis on the radon build-up characteristics and peak concentrations, should also be considered by the ALARA principle.

With these *models,* the radioactive dose equivalent for the university staff and students can be calculated using the SigmaPlot Software[48]. Different scenarios can be simulated as previously-defined in Chapter 5. In our study, five new HVAC Operational Schedules have been explored for individual energy cost savings and subsequent radon peak level exposure due to different sets of running mode (16, 12.5, 11.6, 10.7 and 9.9 Ventilation-on-hours) of the system. These are compared to the existing running practice (12 Ventilation-on-hours). Under these circumstances Operational Schedule No.5, as indicated in *Tables 5-2 and 6-1,* is regarded as an energy-efficient approach to operate the HVAC system of the university with the dual benefit of utility costs saving and a reduction of human exposure to radon. This Schedule No.5 can be employed as a cost-effective way to manage indoor radon concentration by applying the *radon level predictive models (4) and (8)* of Chapter 3.

In order to abide by the ALARA principle, it is necessary to investigate whether the radon exposure associated with Operational Schedule No.5 can be further reduced. *Fig 6-1* is obtained by applying the derived *radon level predictive models* to determine the change in radon radiation dose following a systematic shift of the HVAC on-off pattern. Since the *models* were originally designed specifically for predicting and managing radon concentrations, it does not have the capability of automatically solving for a minimal radon dose (i.e. area under the curve) and in a given time duration. Therefore, an analysis of the effect of discrete incremental shifts has to be carried out by iteration. An hourly, instead of smaller, increment was selected for practical reasons. The results are given in *Fig 6-1*.

By examining the HVAC Operational Schedule No. 5 in *Fig 6-1*, the maximum reduction of mean radon exposure and the consequent reduction of the radioactive dose equivalent for the HKUST occupants can be obtained with a "2-hour Advance" shift (2-hours shifting of the concentration profile to the left, i.e. by starting the HVAC system 2 hours earlier and stopping 2 hours earlier than usual). The estimated radon exposure reduction is about 150 $Bqhm^{-3}$. The "shifted" Schedule No. 5 results in an additional reduction of 9 cancer cases, which corresponds to HK$1.8 Million approximately. As mentioned previously, this is a very rough estimation for reference only.

On the other hand, in the real indoor environment, it is difficult to make a solid decision on the HVAC operational patterns solely based on "dose reduction". There are other factors, such as the operational constraints of switching off the whole HVAC system two hours earlier when thousands of staff and students are still working or studying. As discussed in the 1st Portfolio Submission on "Radon Review", it is a fundamental task of an air-conditioning engineer to control the appropriate quantity and flow of fresh air so as to maintain good indoor air quality of the building environment.

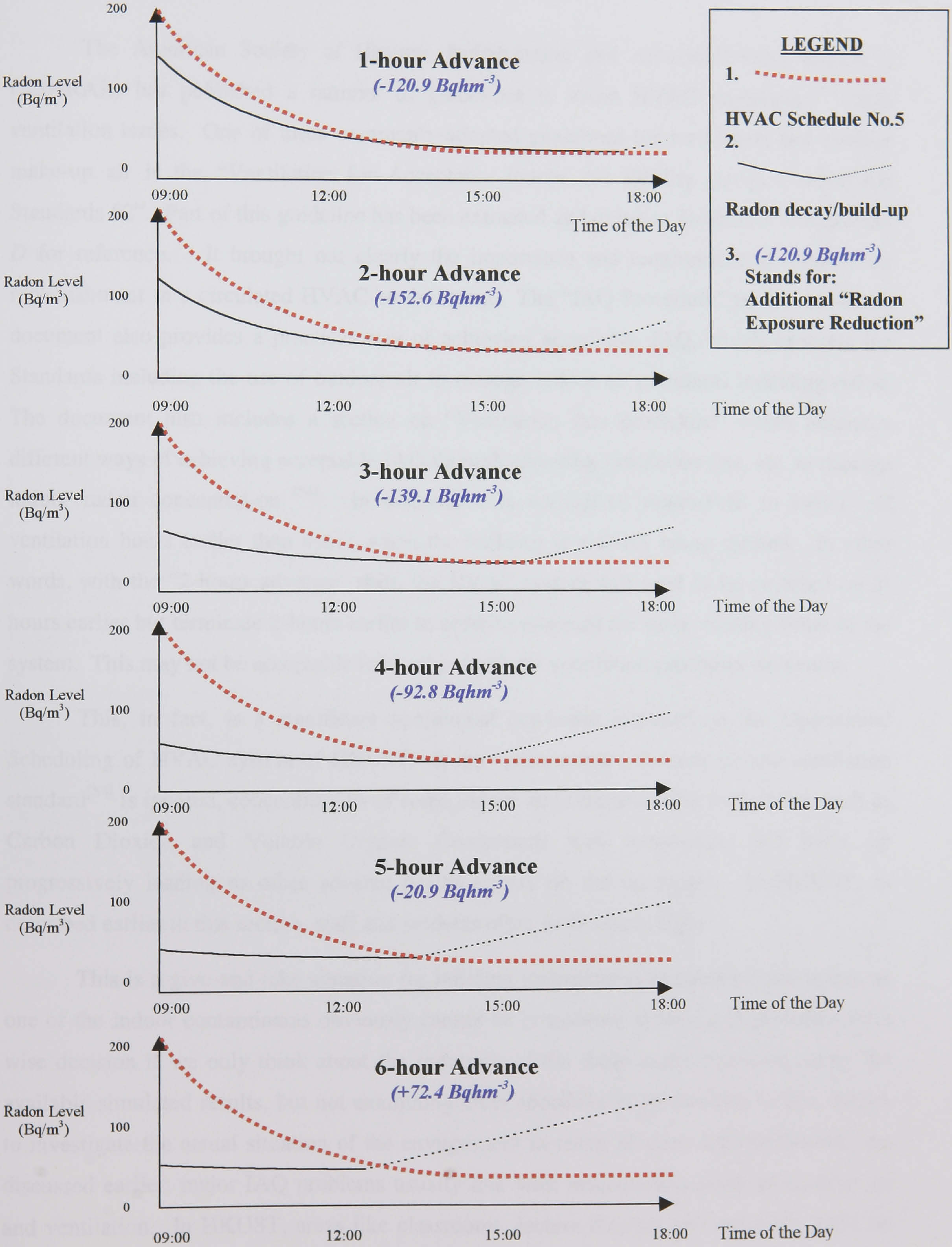


Fig 6-1 Simulated Radon Exposure Reductions by Hourly-Advances of Schedule No. 5

The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) has published a number of guidelines to assist HVAC engineers [54] with ventilation issues. One of these commonly-adopted guidelines for ventilation and outdoor make-up air is the "Ventilation for Acceptable Indoor Air Quality (IAQ) - ASHRAE Standards 62". Part of this guideline has been extracted and given in *Table D-1* of *Appendix D* for reference. It brought out clearly the importance and requirement of outdoor air replenishment in a circulated HVAC environment. The "IAQ Procedure" of the ASHRAE document also provides a practical way of achieving acceptable IAQ, which executes the Standards including the use of outdoor air to manage indoor air pollutants including radon. The document also includes a section on "Ventilation rate procedure" which describes different ways of achieving acceptable IAQ through adjusting ventilation rate, etc. to manage indoor radon concentration [54]. In essence, it is considered impractical to switch off ventilation hours earlier than usual, when the building is actively being utilised. In other words, with the "2-hours advance" shift, the HVAC system will need to be switched on 2-hours earlier but terminate 2-hours earlier in order to maintain the same running hours of the system. This may not be acceptable from a fundamental ventilation provision viewpoint.

This, in fact, is a significant operational constraint imposed on the Operational Scheduling of HVAC system of HKUST. If the recommended outdoor air and ventilation standard[54] is ignored, concentrations of some indoor air pollutants other than radon, such as Carbon Dioxide and Volatile Organic Compounds will accumulate and build up progressively leading to other adverse health effects on the occupants. In HKUST, as described earlier in this section, staff and students often work late at night.

This is a give-and-take situation for building management to consider and radon, as one of the indoor contaminants obviously cannot be considered alone. It is probably not a wise decision if we only think about the reduction of the mean radon exposure, using the available simulated results, but not examining other shortfalls or performing further studies to investigate the actual situation of the environment in terms of other IAQ pollutants. As discussed earlier, major IAQ problems usually link with inadequate amount of outdoor air and ventilation. In HKUST, areas like classrooms, lecture theatres and assembly halls are occupied by a large number of students and staff. Outdoor fresh air replenishment to these areas become even more essential in order to provide a healthy indoor environment for the staff and students.

Another constraint appears in the staff management of the HVAC system if the latter Operational Schedule (i.e. "2-hours Advance") is to be used. As discussed in section 6.4, although the physical ON-OFF control of the HVAC system at HKUST can be performed via the computerised Building Management System (BMS), additional manpower is also required to maintain the additional running machinery in early morning. This affects the operational cost of the system. If daytime workers are to be allocated to the night shift for this purpose, the repair and maintenance workforce in the daytime will be reduced correspondingly. This may affect the overall productivity and effectiveness of day-to-day repair and maintenance work of the building service team.

With all the above constraints considered, the shifting-forward approach (starting and terminating one or two hours earlier) for the HVAC Operational Schedule No.5 appears not to be practicable.

The other alternative of advancing switch-on time WITHOUT early termination of the HVAC System was also explored. Schedule 5 with "1-hour Extension" (i.e. switch on one hour early but without early switch-off as shown in *Fig.6-2*) was used for evaluation and comparison with the previous scenarios. Again, by applying the SigmaPlot Simulator[48], using our developed *radon level predictive models*, the resulting mean radon exposure of the "1-hour Extension" scenario turns out to be 463.7 $Bqhm^{-3}$, which corresponds to a dose reduction of 278.1 (or 741.8 - 463.7) $Bqhm^{-3}$. This translates to approximately 15 cancer cases or HK$3.2 Million savings from the present way of operation ("now" as shown in *Table 4-1* and *6-1*). However, at the same time, the previously calculated utilities saving will be reduced by half because of the longer running hours of the HVAC system. A cost-benefit analysis finds that greater overall financial benefit can be achieved by this "1-hour Extension" Schedule No.5 operation mode (with 2.7/2 + 3.2 or 4.55 Million HK Dollars) compared with "Schedule No. 5" (with 2.7 + 1.5 or 4.2 Million HK Dollars). The net dollar gain is HK$0.35 (or 4.55 – 4.2) Million approximately.

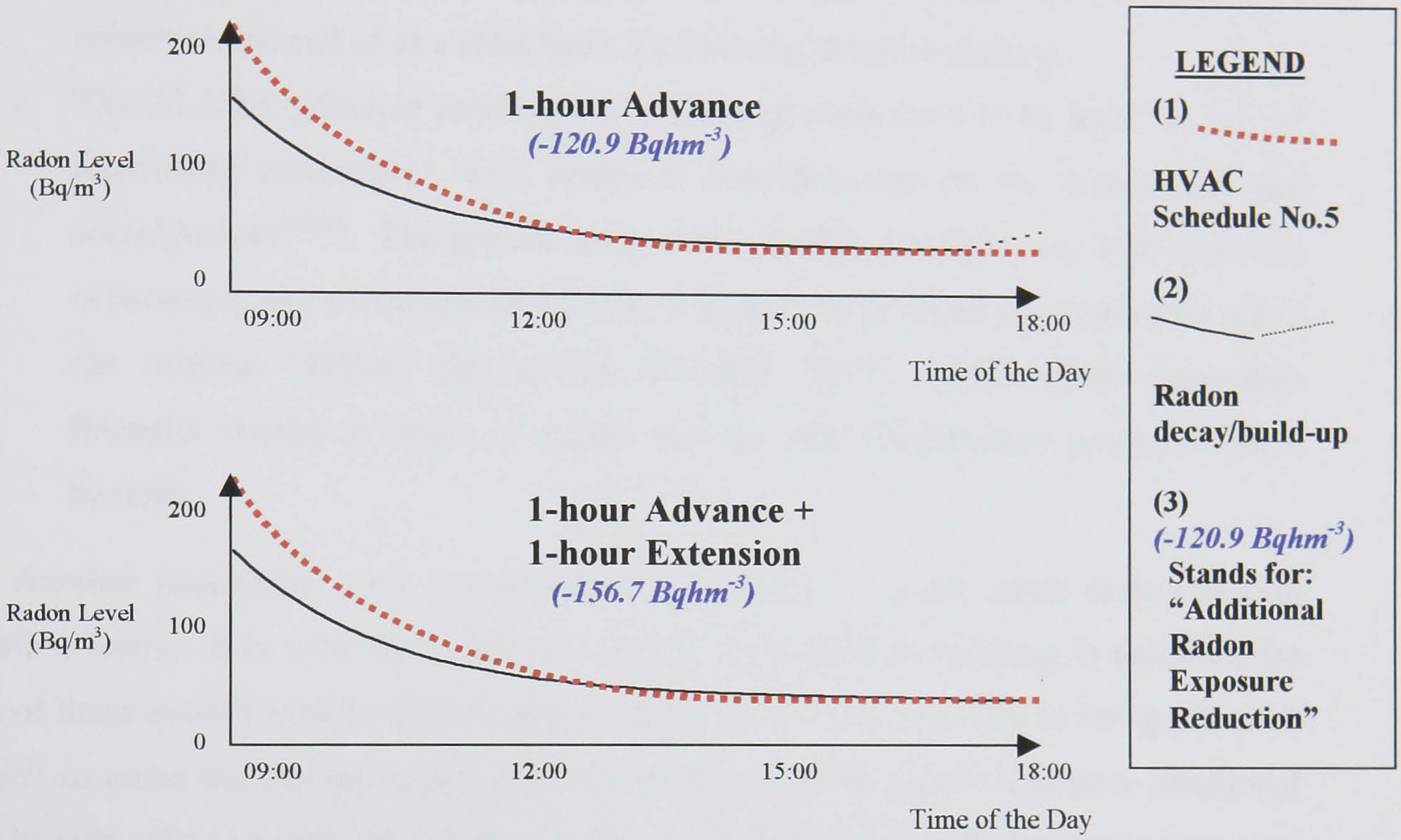


Fig 6-2 Radon Exposure Reductions for 1-hour Extension after 1-hour Advance of Schedule No.5

However, the net benefit of HK$0.35 Million of financial saving due to this new operational mode may not be significant considering the uncertainties when converting life savings to dollar figures. The feasibility of the "1-hour Extension" Schedule No.5 is also affected by the risk of demoralising the staff, i.e. due to the change of HVAC Operation, some staff need to report to duty earlier than usual.

Taking all these into consideration, the original HVAC Operational Schedule No. 5 is still recommended. The major reasons are:

a. From an engineering viewpoint, the immediate reward due to higher energy savings is preferred. The dollars gain can be used to carry out more studies, which can involve subsequent environmental benefit due to "reduced energy" and hence "reduced environment impacts" etc.

b. On the other hand, there is a comparatively long duration of return in human lives savings' consideration. Moreover, many other uncertainties influence the overall estimating process, such as the social values of human lives. As discussed previously, the human lives saving in dollar's figures are perhaps best used as a reference, instead of as a solid basis for financial decision making.

c. The ALARA principle requires that radon exposures have to be kept "as low as reasonably achievable", with sufficient *considerations on the economical and social factors*[4][46]. The present study abides by this principle, and with elaborate economical and social considerations, it appears to be more appropriate to select the original "HVAC Operational Schedule No.5", which gives immediate financial returns in terms of energy savings with considerable potential health benefits.

Another possibility worth considering is to ventilate a pulse mode during system termination hours. It is very likely that in systems where frequent pulsing is possible, the benefit of these *models* may be further enhanced. In theory, one can refer to the application of *models* to pulse the system during the overnight build-up of radon to achieve additional overall benefit. For example, the HVAC system can be set to be actuated upon the detection of a specific level of radon build-up and to be turned off once the level falls below certain set point. It, thus, would appear that exercising this operational characteristic of the HVAC installations might play an important role in optimisation of cost-effectiveness and health benefit approaches.

However, while more frequent pulsing of the system may yield additional benefit, the design of the HVAC installations does not always allow for such fine manipulation. Most large HVAC systems in the current market require several hours of down time in between operations for stabilisation purposes. An increased number of start-ups within a short period of time may adversely affect the flow characteristic of the system coolant and may overheat the electric-driven motors of the HVAC installations. In fact, the environmental conditions, such as humidity and temperature, and capacity of each HVAC plant room housing will also complicate the issue. For an enormous HVAC system like that of HKUST, the ability to perform this pulsing operation is severely limited and the option is therefore not practical enough to be further pursued in this study.

6.12 Further Works Possible

While this project focuses on managing radon concentrations cost-effectively, one must realise that there are other indoor pollutants, such as carbon dioxide, particulate, volatile organic compounds and other contaminants. To manage all these indoor air pollutants effectively, one might consider integrating models of other air pollutants into the radon level predictive *models* derived from this project to produce a comprehensive IAQ model. Alternatively, individual parameters for managing different indoor air pollutants can be addressed by a computerised building management system (BMS). This integration can optimise the balance of IAQ concern and energy conservation. This is in fact an important development direction for BMS nowadays for HVAC facilities.

The *radon level predictive models* can also be further fine-tuned by applying them in different geographical locations where radon concentrations are affected by other "structural characteristics" and "climatic conditions" etc. This can further enhance the accuracy and applicability of the *models.*

The durability of Polyurethane-based paint coating (as discussed in *Section 6.7*) depends on a number of parameters such as the cleanliness of the wall surface, the type of primary base coating, the trapping capability of coating for air and water, the coating thickness, the adhesive properties of paint, etc. Studies to optimise these parameters in producing a long lasting radon paint sealant should be conducted to enhance the performance and applicability of the *models* derived.

Further investigations on the feasibility of different HVAC installations to allow for pulsing operation can be conducted. These involve parameters of choice of air-cooled versus water-cooled compressors, system coolants, capacities of HVAC machines and auxiliaries, environmental conditions requirements, sizes of plant room, various driving power designs etc. The results of these additional studies can further enhance the performance and applicability of the *models* and, as a result, will provide better information to the manufacturers in the optimal design of future HVAC systems.

Chapter 7

CONCLUSIONS

1. The distribution of radon concentrations observed at the Hong Kong University of Science & Technology (HKUST) matches well statistically with the community data reported by the Hong Kong Environmental Protection Department (HKEPD). This produces good evidence of the representation of the *radon level predictive models* derived from the studies and applicability for common usage.

2. With the good correlation between the real-time, active radon sampling results and passive sampling results, an inexpensive charcoal canister system for simple radon monitoring has been explored. All these measurements appear to be useful to adopt in a general heating, ventilating and air-conditioning (HVAC) environment such as HKUST.

3. The results indicate the vast majority of the measured average radon concentrations (107 Bq/m^3) at the Hong Kong University of Science & Technology (HKUST) are approximately within 50% the Action Level set by the World Health Organisation's (WHO) recommended level (200 Bq/m^3). However, about 10% of the readings were in excess of this WHO limit. Forty-six percent of these rooms also showed average peak radon concentrations (264 Bq/m^3) which substantially exceeded this WHO limit.

4. In reducing the cumulative time for the HKUST community in exposure to the intermittent high indoor radon concentrations, it is reasonable to study the radon build-up characteristics and peak concentrations. However, the radiation protection principle of ALARA (as low as reasonably achievable) is also important to be

considered in monitoring the overall cancer risk of the population. The majority of the campus population spends most of its time everyday in the indoor HVAC environment. Another factor is that the radon level here in HKUST has been measured at a high mean of approximately 100 Bq/m^3, exceeding twice the global average as reported by international bodies of radiation protection.

5. Indoor radon level was found to increase in linear progression when the heating ventilating and air-conditioning (HVAC) system was switched off but decrease exponentially after the system resumed operation. Using a test chamber simulating the HVAC environment, a *model* was formulated successfully to predict its concentrations, using the derived radon diffusion characteristics. This exercise required the inclusion of a modification factor, M to account for the radon sink effect. A pre-existing concentration predictive model for Volatile Organic Compounds (VOC) was identified and successfully modified to simulate the HVAC environment of HKUST in predicting the indoor radon concentrations, $C_{(t)}$. The results indicate the modified *radon level predictive models* are capable of correlating well with field data.

6. The *radon level predictive models* derived in this study are recorded below:

   a. *Radon Concentrations at time t during the HVAC system is OFF*:

   $C_{(t)} = C_o + RLt$ (*model (4)* of Chapter 3)

   The accumulation of indoor radon, $C_{(t)}$ at any time t after the HVAC has been terminated can be identified using the above *model (4)* which considers the relationship among the original indoor radon concentrations, C_o; the radon emission, R; the physical characteristics of the indoor environment, L and the period of time after the HVAC was switched off, t.

b. *Radon Concentrations at time t after the HVAC system is ON:*

$$C_{(t)} = \frac{RL}{MN - k}[\exp(-kt)-\exp(-MNt)]+(C_{o'}-C_{in})\exp(-MNt) + C_{in}$$

(*model (8)* of Chapter 3)

Where, Modifier $M = 0.65 - 0.1N$

(*model (9)* of Chapter 3)

The concentrations of indoor radon, $C_{(t)}$ at any time t after the HVAC system has resumed can be identified by using the above *models (8)* and *(9)* which consider the relationship among the original indoor radon concentrations, $C_{o'}$; the radon emission, R; the physical characteristics of the indoor environment, L; the intake fresh air radon concentrations, C_{in}; the source decay rate, k; the modifier of the *models*, M; the air exchange rate and the period of time after the resumption of HVAC system, t.

For the case of our room chamber study as described in Chapter 3, the parameters of *model (8)* are:

$C_{(t)}$	is radon concentration as a function of time (mg/m^3)
R	is 8.60 $Bq/m^2/hr$ (radon emission rate from room chamber surface)
L	is 1.81 m^2/m^3 (loading factor), L = S/V
N	is 0.30, 0.52, 1.11, 2.08 and 4.22 /hr (air change rate per hour)
k	is 0.01 /hr (radon decay rate)
t	is 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 hr (v-on-hours)
$C_{o'}$	is 351 (N = 0.30), 278 (N = 0.52), 242 (N = 1.11), 236 (N = 2.08) and 242 (N = 4.29) Bq/m^3 (initial room concentration of radon)
C_{in}	is 15 Bq/m^3 (radon background concentration in fresh air)
M	is the modification factor, where, M = 0.65 – 0.1N

Then, The *radon level predictive models* for Vent-off-hrs and Vent-on-hrs become, respectively,

$C_{(t)}$ (Vent-off-hrs) = $C_o + 1.55t$, and

$$C_{(t)}\ (\text{Vent-on-hrs}) = \frac{1.55}{MN - 0.01}[\exp(-0.01t) - \exp(-MNt)] + (C_{o'}-15)\exp(-MNt) + 15$$

7. The derived HK$2.7 and 5 Million of total annual energy saving potential, after implementation of the respective cost-effective *Active* and *Passive Radon Control Approaches* via Cost-effective HVAC operational scheduling and P-u paint coverings, is attractive in an economical sense. Both *Approaches* are successful in providing energy-efficient measures to address the indoor radon concentrations of a HVAC environment. However, the P-u painting project under *Passive Radon Control Approach* required HK$57 Million with a payback period of 10 or 13 years respectively using the Simple Payback Period Method or Discounted Payback Period Method.

8. The overall results of executing the established *radon level predicative models* together with the developed radon management strategies are encouraging in achieving an acceptable radon concentration at the best energy efficiency. The energy-efficient radon management strategy developed under the *Passive Control Approach* can be further explored in a direction to cater for the indoor areas with high radon emission source. This study has confirmed the advantage, regarding indoor radon reduction measures, that an additional layer of Polyurethane-based paint on the internal surfaces of the HVAC building environment can promote the effectiveness of radon emission reduction from radon sources.

9. To further evaluate the potential benefit of the derived radon control strategies, the radon exposure reduction for the HKUST occupants resulting from this EngD study has been converted into effective dose reduction from a radiation protection viewpoint. These were further translated into reduction in number of potential cancer cases and in dollar figures. The exercise demonstrated the significant health benefit associated with this work.

10. In order to justify the cost-effectiveness of the selected control strategies, the *radon level predictive models* were used to simulate dose reduction under different ventilation conditions, and to identify an optimal ventilation schedule. This process successfully justified the use of the derived HVAC Operational Schedule (No.5) as an energy-efficient approach to "best" manage radon risk in accordance with the ALARA principle.

11. Employing cost-effective strategies to manage radon and other indoor air pollutants in a HVAC environment are critical areas among recent safety, health and environmental management research. This is due, in a large part, to improvements in human living standards and that people are more informed about health and environmental impacts. The overall result of this Engineering Doctorate research is extremely useful in that it has wide applicability. The findings demonstrate strong potential for wide application of the knowledge derived from this project to other facilities in enhancing a healthier indoor environment.

APPENDICES

Appendix A: Description of RAD-7 Continuous Radon Gas Monitor

In the radon decay chain, Polonium 218 (the first daughter) has a half-life of 3.05 minutes, and decays with a 6.00 MeV alpha particle. The Polonium 214 appears some 45 minutes later and generates a 7.69 MeV alpha particle. Therefore, an instrument for the radon research was required to filter out all pre-existing radon daughters and accept only radon gas into the measurement chamber. It should be able to capture the Polonium 218 atoms created in the measurement chamber and discriminate between the 6.00 MeV alpha particles from the Polonium 218 and the 7.69 MeV alpha particles arising from the Polonium 214 much later. The RAD-7, an U.S. manufactured radon gas continuous measuring device[55] can fulfil the above requirements giving proper time resolution for the radon measurements..

The RAD-7 has been used widely in academic and research institutions of Hong Kong[56]-[58]. The solid state instrument pulls samples of air through a fine inlet filter into a chamber for analysis. The filtered air decays inside the chamber producing detectable alpha emitting progeny, particularly the polonium isotopes. The solid state detector converts alpha radiation directly to an electrical signal using alpha spectrometry technique which is able to distinguish radon from thoron and signal from noise[55].

The RAD-7[55] has several modes of operation and in one, "sniff Mode", it counts only the 6.00 MeV alpha particles produced by the short-lived Polonium 218 and thus has a response time of about 10 minutes for a 90% response to a step change in radon concentration, either up or down. During a linear ramp lasting several hours, the ten-minute response time has the effect of delaying the readings by ten minutes but does not alter the slope of the ramp, which is the parameter of interest.

Operational Procedures[55] of the RAD-7 were also extracted from the user manual to better understand the actual operation of instrument. They are given below:

1. *Attach the short vinyl tubing to inlet filter*
2. *Attach filter onto the air inlet stem*
3. *Remove both end caps from the small drying tube containing blue desiccant granules*
4. *Attach small drying tube to other end of the short tubing*
5. *Position the HP printer between the green lines on the top panel*
6. *Turn on printer by sliding left switch to "On" position*
7. *Connect AC power cable (with adapter cord and 3-day battery charger)*
8. *Turn "On" RAD7 by throwing Rocker Switch on tope panel to the "On" position*
9. *Check at display screen of the RAD7, which should show model/serial number of equipment, calibration date, last used date/time and current time date/time etc.*
10. *Press "Arrow", "Enter" and select options in "Menu" for continuous measurements*

For the external appearance of the instrument, please also refer to *Fig 2-1* of Chapter 2. The RAD-7 Continuous Radon Gas Monitors, although manufactured in the USA, used in this studies had been factory-modified electronically to provide data in SI units in stead of pCi/l to suit the Hong Kong market. All printouts retrieved from the Monitors showed radon measurements in unit of Bq/m^3 instead of pCi /l. A sample printout from RAD-7 also given below:

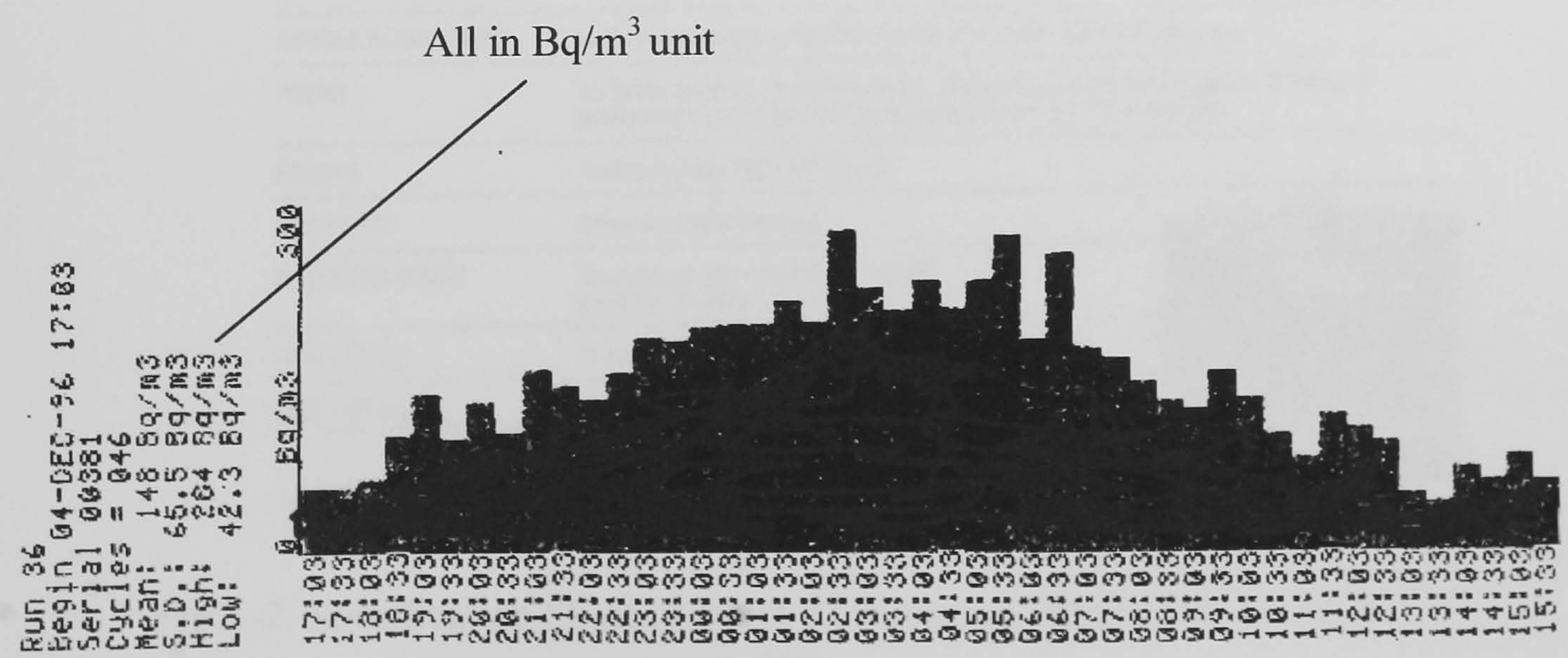


Fig A-1 Sample printout from RAD-7 Continuous Radon Gas Monitor

The Rad7 used in this study had been factory- modified to deliver data in SI unit of Bq/m^3

RAD7 SPECIFICATIONS

MULTI-MODES	Continuous Radon Gas Monitor Long-term/Short-term Screener Sniffer: With long tube "snout" to search for radon levels and gushers
MULTI-MEASUREMENTS	Measures radon in air, soil, and water (with new H_2O accessory)
SENSITIVITY	Monitor: 0.4 counts/min/pCi/L Sniffer: 0.2 counts/min/pCi/L
RANGE	0.1 — >20,000 pCi/L
MEMORY	1,000 previous radon concentrations and times (50 complete data sets including spectra and times). Can be read out on LCD or printed out. Also shows total elapsed time, high, low, and average of previous readings.
PRINCIPLE OF OPERATION	Electrostatic collection of alpha emitters with spectroscopic analysis
BUILT-IN AIR PUMP	Flow rate: Nominal 1 liter/min Filter: Input air filter, inlet & outlet air connections
SPECTRUM READOUT*	Pulse height spectrum of alpha distribution verifies radon/thoron, and also shows the ***RAD7*** is operating properly. Accurate determination of the alpha particle energies produces a radon signature that allows discrimination of radon and thoron's alpha particles from those of other isotopes.
FAST LOW-LEVEL READINGS*	In Continuous Monitor mode, ***RAD7*** measures the EPA action level of 4 pCi/L in just 1 hour (60 minutes), with standard deviation of 10%. Since the ***RAD7*** has virtually no background, it is much more sensitive than other electronic detectors, easily measuring down to 0.1 pCi/L.
RECOVERY IN MINUTES*	Recovers from high radon exposure with a 3.05 minute half-life: to less than 10% of peak value in 12 minutes; to less than 1% of peak value in 30 minutes. *Drops from 20,000 to 1 pCi/L in 8 hours.*
TAMPER-PROOF*	A "Test Lock" command is programmed into the machine to secure your ***RAD7*** against all kinds of intentional or unintentional tampering.
AUTO MODE*	This setting starts a test run in Sniff mode, then switches to Normal mode after the first 3 hours. No more waiting for equilibrium. Gives quick response, followed by statistical precision.
CONTINUOUS UPDATING*	Gives continuous update of radon levels so you can see the trend at all times, not just at pre-set intervals.
COMPUTER LCD DISPLAY	2 line x 16 character, alpha-numeric. Easy to read.
AUDIBLE RADON COUNT	Indicates presence and intensity of radon and thoron. May be turned on or off.
POWER	AC/Battery powered - 5 AH 6V batteries. Automatic charge when plugged in. Continuous battery operation: 24 hours in Sniffer mode; 72 hours in Monitor mode.
PRINTER	Hewlett-Packard Model HP 82240A
RS232 PORT	Computer/modem hook-up
OPERATING RANGE	Temperature: 40° - 105° F. (5° - 40° C.) Humidity: 0 - 80%
WEIGHT/SIZE	11 pounds complete - 9.5" x 7.5" x 10.5"
CASE MATERIAL	High density polyethylene

Hewlett-Packard Printer.

* ***RAD7*** **exclusive feature**

Hewlett-Packard is a registered trademark of the Hewlett-Packard Company.

Fig A-2: Specification Sheet of RAD-7 Continuous Radon Gas Monitor (Niton Corporation, U.S.A.) [55]

Appendix B: Comparing HK Radon Levels With Other Countries

Classification of areas	*Radon Concentration (Bq/m^3)*
Residential	86
School	83
Office	140
Factory	115
Public Place	106
Hospital	42
All Premises	*98*

Table B-1. Daily Average Radon Levels in Hong Kong as reported by HKEPD[26]

Country	*Year set*	*Existing Dwellings*[a]	*Future Dwellings*[a]
Australia	1990	200 Bq/m^3 (5 pCi/l)	200 Bq/m^3 (5 pCi/l)
Austria	1992	400 Bq/m^3 (11 pCi/l)	400 Bq/m^3 (11 pCi/l)
Belgium	1995	400 Bq/m^3 (11 pCi/l)	400 Bq/m^3 (11 pCi/l)
Canada	1988	800 Bq/m^3 (22 pCi/l)	800 Bq/m^3 (22 pCi/l)
Finland	1992	400 Bq/m^3 (11 pCi/l)	200 Bq/m^3 (5 pCi/l)
Germany	1988	250 Bq/m^3 (8 pCi/l)	250 Bq/m^3 (8 pCi/l)
Ireland	1991	200 Bq/m^3 (5 pCi/l)	200 Bq/m^3 (5 pCi/l)
Luxembourg	1992	150 Bq/m^3 (4 pCi/l)	150 Bq/m^3 (4 pCi/l)
Netherlands	1994	20 Bq/m^3 (.5 pCi/l)	20 Bq/m^3 (.5 pCi/l)
Norway	1988	800 Bq/m^3 (22 pCi/l)[b]	200 Bq/m^3 (5 pCi/l)
Sweden	1994	400[c] /200[d] Bq/m^3 (11[c]/5[d] pCi/l)	200 Bq/m^3 (5 pCi/l)[c]
Switzerland	1994	1000[c] /400[d] Bq/m^3 (55[c]/11[d] pCi/l)	400 Bq/m^3 (11 pCi/l)[c]
United Kingdom	1990	200 Bq/m^3 (5 pCi/l)	200 Bq/m^3 (5 pCi/l)
United States	1988	150 Bq/m^3 (4 pCi/l)	Same as outdoors

Table B-2 Reference and Action Levels in 14 Different Countries (in Bq/m^3 and pCi/l)[27]

Where,

[a]*Reference levels for dwellings with the except of those marked with* [c and d]*;*

[b]*Remediation, in range 200-800 Bq/m^3, should cost less than US $400;*

[c]*Regulatory Limit; and*

[d]*Recommended upper limit for remediation*

Appendix C: Payback Calculation for HKUST P-u Painting Project

Various measures can be used for this evaluation of the payback periods of the project systems. Some of the criteria to be considered include the following:

- Simple Payback Period
- Discounted Payback Period

For the P-u painting project using the *Passive Radon Control Approach*, the following assumptions are required to be made for computing the payback period of the project:

I. Investment for the P-u painting project is \$57M (as derived in Chapter 5)

II. Budget cost for routine painting of university campus in the first year is 0.5M with an annual budget increase of 3%.

III. Cost savings per year - HK\$5.6M annually with estimated inflation 3% (e.g. increase of energy price)

IV. Net Cost for minor repair = HK\$0.1M per year (to be increased with inflation)

V. Net Extra Cost incurred due to additional maintenance labour required during project per minor repair = HK\$0.05M per year with annual increase of 5%.

VI. Taxation rate = (neglected due to government-funded university)

VII. Interest rate = 4% (a very rough estimate due to economic recession. The previous average is around 8%[56]).

VIII. Inflation rate = 3% (a very rough estimate due to economic recession. The previous average is around 9%[56]).

Using a Simple Payback Period Method (SPPM), the length of period for this Polyurethane-based Painting Project can be estimated as shown in *Tables C-1 to C-3*. However, if a Discounted Payback Period Method (DPPM) is used, the length of period for the project can be estimated as shown in *Tables C-4*.

HK$INCREMENTAL CASH OUTFLOWS (ICO)			
Year	***Maintenance (IV) & (VIII)***	***Labour (V)***	***ICO***
1	0.10M	0.05M	0.15M
2	0.10M	0.05M	0.15M
3	0.11M	0.06M	0.17M
4	0.11M	0.06M	0.17M
5	0.11M	0.06M	0.17M
6	0.12M	0.07M	0.19M
7	0.12M	0.07M	0.19M
8	0.12M	0.07M	0.19M
9	0.13M	0.07M	0.20M
10	0.13M	0.08M	0.20M

Table C-1 Calculation of Incremental Cash Flow for P-u Painting Project

HK$OPERATING CASH FLOW (OCF)			
Year	***Cash Inflow (III)***	***Cash Outflow***	***OCF***
1	0	0.15M	0.15M
2	5.07M	0.15M	5.22M
3	5.22M	0.17M	5.39M
4	5.37M	0.17M	5.54M
5	5.54M	0.17M	5.71M
6	5.71M	0.19M	5.90M
7	5.88M	0.19M	6.07M
8	6.05M	0.19M	6.24M
9	6.24M	0.20M	6.44M
10	6.42M	0.20M	6.62M

Table C-2 Calculation of Operating Cash Flow for P-u Painting Project

		HK$NET CASH FLOW (NCF)		
Year	***Incremental Cash Flow***	***Cash inflow (II)***	***Cash Flow***	***NCF***
0	(57M)	-	(57M)	(57M)
1	0	0.5M	0.5M	(56.5M)
2	5.07M	0.52M	5.59M	(50.91M)
3	5.22M	0.53M	5.75M	(45.16M)
4	5.37M	0.55M	5.92M	(39.24M)
5	5.54M	0.56M	6.10M	(33.14M)
6	5.71M	0.58M	6.29M	(26.85M)
7	5.88M	0.60M	6.48M	(20.37M)
8	6.05M	0.62M	6.67M	(13.7M)
9	6.24M	0.64M	6.88M	6.87M
10	6.42M	0.67M	7.09M	-

Table C-3 Calculation of Net Cash Flow for P-u Painting Project

Therefore, the payback period of the HKUST P-u Painting Project using SPPM is estimated:

9 + [(57–0.5–5.59–5.75–5.92–6.10–6.29–6.48–6.67– 6.88) / 7.09] years

= <u>10 years</u>

HK$ NET PRESENT VALUE (NPV) OF PROJECT

Year	*Cash flow*	*PVIF (4%)*	*Present Valve PV*	*NCF*
0	(57M)	-	-	(57M)
1	0.5M	0.96	0.48M	(56.52M)
2	5.59M	0.92	5.14M	(51.38M)
3	5.75M	0.88	5.06M	(46.32M)
4	5.95M	0.85	5.05M	(41.27M)
5	6.1M	0.82	5.00M	(36.27M)
6	6.29M	0.79	4.97M	(31.3M)
7	6.48M	0.76	4.92M	(26.38M)
8	6.67M	0.73	4.87M	(21.51M)
9	6.88M	0.70	4.82M	(16.69M)
10	7.09M	0.66	4.68M	(12.01M)
11	7.31M	0.63	4.61M	(7.4M)
12	7.52M	0.61	4.59M	(2.81M)
13	7.75M	0.59	4.57M	

Table C-4 Calculation of Net Present Value for P-u Painting Project

[Where, Present Value Factor stands for the Present Value of $\$1(1+r)^{-n}$]

The Payback Period of the HKUST P-u Painting Project using the DPPM is estimated:

12 + [(57-0.48-5.14-5.06-5.05-5.0-4.97-4.97-4.92-4.87-4.82-4.68-4.61–4.59) / 4.57] years

= 13 years

Appendix D: Guidelines for Ventilation and Outdoor Air Requirement

Application on commercial and institutional facilities	*Estimated Maximum Occupancy (per 1000 ft^2 or $100m^2$)*	*Outdoor Air Requirement in cfm /person (l/s.person)*	*Outdoor Air Requirement in cfm/ft^2 (l/s.m^2)*
Commercial dry cleaner	30	30 (15)	-
Hotel Bedrooms	-	-	30 (15)
Hotel Living rooms	-	-	35 (18)
Public corridors	-	-	0.05 (0.25)
Office Space	7	20 (10)	-
Smoking Lodge	70	60 (30)	-
Conference Room	50	20 (10)	-
Laboratories	30	20 (10)	-

Table D-1 ASHRAE Guidelines for ventilation and outdoor air [59]

Where, cfm, cu.ft.per minute and l/s, litre per second, are the units of ventilation rates.

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